BASIC THEORY OF VOLTAGE REGULATED POWER SUPPLIES

33-60

kepco Inc. 131-38 SANFORD AVENUE • FLUSHING 52, N. Y. • Area Code 212 IN 1-7000 • TWX # NY 4-5196

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NOTES ON INTRODUCTORY LECTURE ON KEPCO VOLTAGE REGULATORS

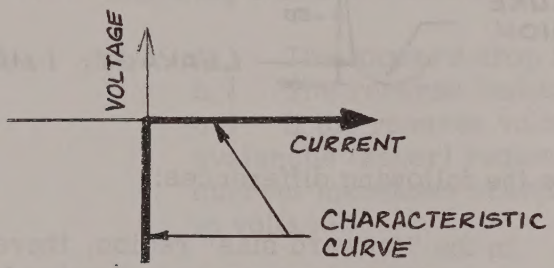
I. Semiconductor devices as circuit elements.

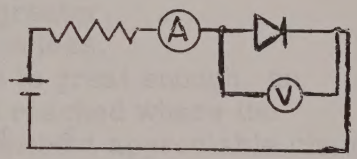
A. The Semiconductor diode.

1. A perfect semiconductor diode is defined by the fact that it conducts perfectly when voltage of one appropriate polarity is applied across its terminals, but when the polarity of the voltage is reversed, no conduction takes place.

a. When the polarity of the applied voltage causes the diode to conduct, the device is said to be "forward biased"; if the polarity is such that no current flow takes place, the device is said to be "reverse biased".

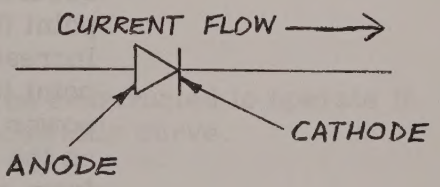
b. The Volt-Ampere Characteristic Curve of a perfect semiconductor diode would be as follows:





Note that when the applied voltage "forward biases" the diode, the device has no voltage drop across it, and hence no effective resistance. Also note that when the applied voltage "reverse biases" the diode, the device exhibits infinite resistance, analogous to an open switch, and no current flows.

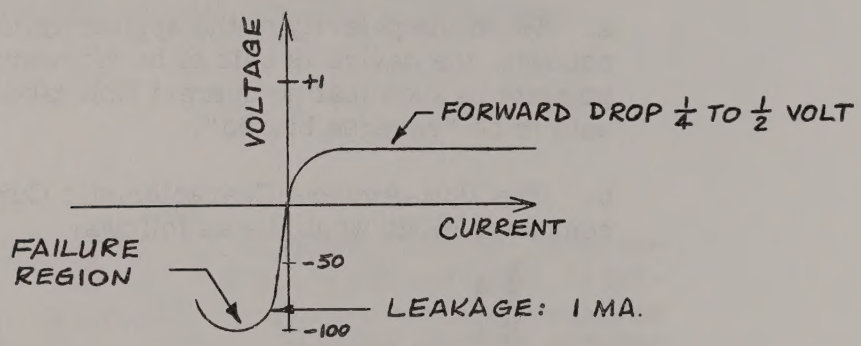
c. The symbol for a diode is:



The arrow indicates the direction of "easy" or "forward" current flow. For current to flow in this direction, the applied bias must be positive at the anode with respect to the cathode.

2. Germanium diode

a. The Volt-Ampere curve for a diode made from a practical material such as germanium is considerably different from the ideal or perfect type just considered.



b. Note the following differences:

1.) In the "forward bias" region, there is now some voltage across the terminals indicating it is not a perfect conductor, but has some resistance. This voltage is called the "forward drop" of the diode.

2.) In the "reverse bias" region, some current flows as the reverse voltage is increased. This is called the "reverse leakage current" of the diode. It increases with temperature, as well as voltage.

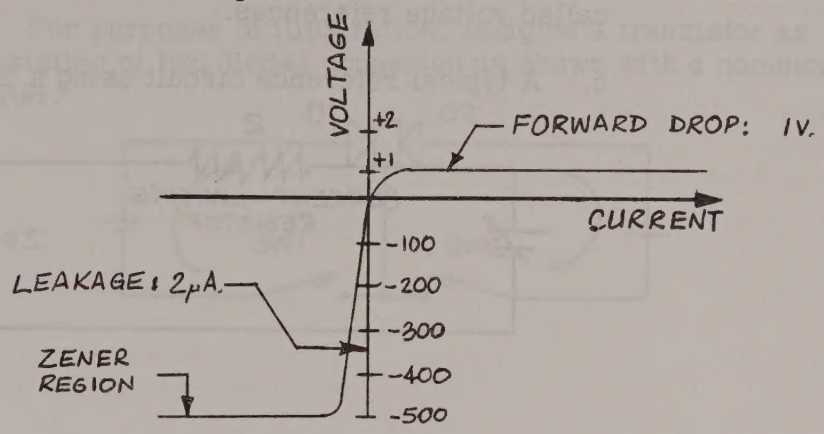
3.) In the region marked "failure", a runaway effect occurs. As the reverse voltage is increased to a critical point (bottom of the curve) the current will continue to increase even with lower applied voltage once the critical point is reached. Since there is resistance present, power is dissipated in the diode in ever increasing amounts as the current increases, until the diode destroys itself from excessive dissipation. Excessive forward current may also destroy the diode by excessive heating.

4.) Typical ratings of germanium diodes:

PIV:	100 v
Forward Drop	0.3 v
Max. Forward Current (average)	250 ma
Max. Junction Temp.	85°C.

3. Silicon diode

a. The Volt-Ampere curve for a diode made of silicon:



1.) Silicon diodes differ from germanium diodes in the following characteristics:

a.) The forward drop is greater.
b.) The reverse leakage is less.
c.) If the reverse voltage is great enough, an avalanche (zener) region is reached where the current increases sharply without appreciable change in voltage.

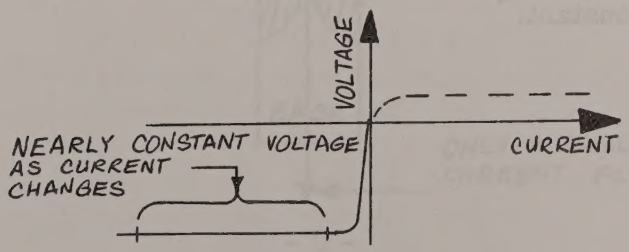
2.) Typical ratings of the silicon diode are:

PIV	500 v
Forward drop	1 v
Max. Forward Current	500 ma
Max. Junction Temp.	150°C.

3.) The silicon diode can also be destroyed by excessive current in either direction.

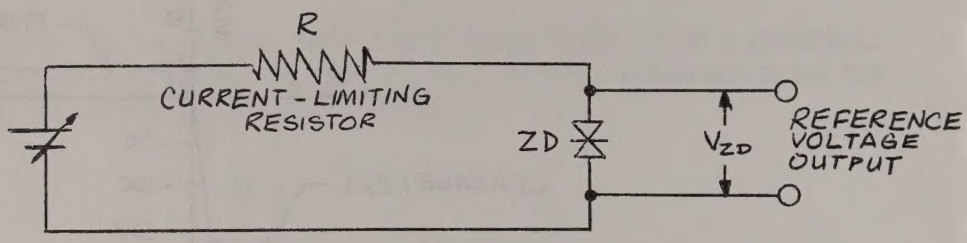
4. The Zener Diode

a. Semiconductor diodes may be constructed to operate in the Zener region of their characteristic curve.



b. In the Zener region, the diode maintains an almost constant voltage across itself even with varying current. Therefore Zener diodes are used extensively as sources of steady voltage, usually called voltage references.

c. A typical reference circuit using a Zener diode:



d. The voltage regulating action of the Zener diode can best be illustrated with the following example:

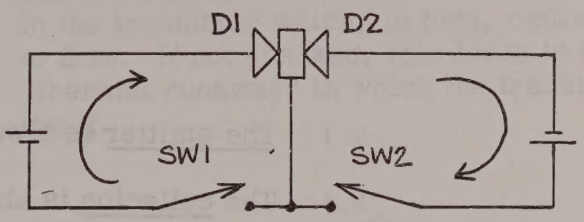
Assume E = 106 v R = 10K Vzd = 6.0 v Rzd = 10 ohms. Approximately 10 ma of current will flow around the loop. However, if E is increased from 106 v to 126 v (an increase of 19%), approximately 12 ma of current will flow. Since the Zener impedance is so low, the change in voltage across it due to the 2 ma increase in current is only 10 x .002 = 0.02 volt. Thus a 19% change in supply voltage gives rise to only a 0.3% change in Zener voltage.

e. Zener diodes are made to operate at almost any Zener voltage between approximately 3 volts and 300 volts.

f. Zener diodes are temperature sensitive, however, to overcome this difficulty, two diodes are matched and connected back to back to form a "double anode construction." One diode section works as a true Zener while the other is connected to be forward-biased. When the temperature rises, the Zener voltage of the Zener section rises, but the drop in voltage across the forward biased section decreases. Thus, the entire unit compensates itself for temperature changes, and the total voltage across it stays constant.

5. The Transistor

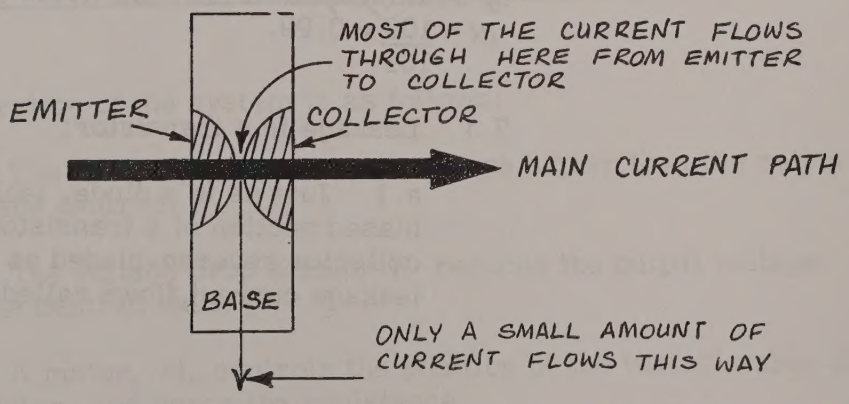
a. For purposes of illustration, imagine a transistor as consisting of two diodes connected as shown with a common center.



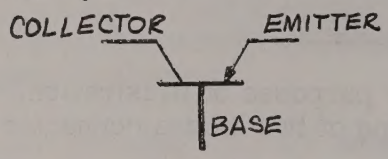
1.) With SW1 closed, current will flow around the first loop through D1 because it is forward-biased by the battery.

2.) If SW1 is opened and SW2 is closed, no current will flow through the second loop through D2 (except perhaps a small amount of leakage current) because it is reverse-biased by the second battery.

3.) However, transistor action takes place when both switches are closed. Note that the two batteries are in a series-aiding connection around the outside loop. The current now flows in one main path around the outside, with only a small amount going around loop 1 alone. The reason this happens is that the straight-through path for current flow through the transistor is the easier path:


MOST OF THE CURRENT FLOWS THROUGH HERE FROM EMITTER TO COLLECTOR
EMITTER
COLLECTOR
MAIN CURRENT PATH
BASE
ONLY A SMALL AMOUNT OF CURRENT FLOWS THIS WAY

4.) The symbol for the transistor is



a.) The emitter is always the forward-biased diode.

b.) The collector is always the reverse-biased diode.

c.) Current flow, if present, is always in the direction of the arrow of the emitter.

5.) This current is controllable, as in a vacuum tube. By controlling the amount of the base current, the "straight through" or collector current, is controlled. The ratio of collector current to base current is called the "Current Gain" of the transistor, denoted as "β" (Beta).

$$\beta = \frac{I_c}{I_b}$$

For example, if 1 ma of I_b permits 100 ma of I_c to flow, the β is 100. This quantity is a constant of the transistor and does not vary with the circuit.

6.) Another definition of current gain is the ratio of Collector current to emitter current.

$$\alpha = \frac{I_c}{I_e}$$

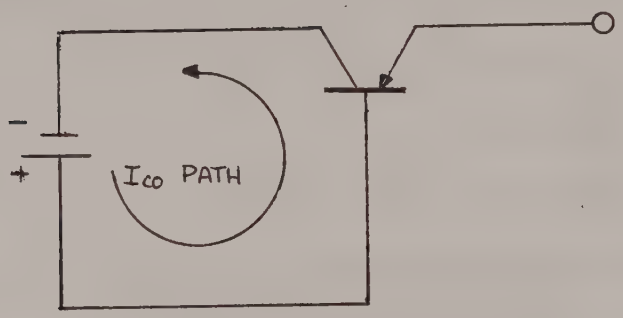
In the previous example, if I_c was 100 ma and I_b was 1 ma, I_e would have to be 101 ma (from Kirchhoff's laws) and $\alpha = \frac{100}{101} = 0.99$.

7.) Leakage in a transistor:

a.) Just as in a diode, leakage occurs in the reverse-biased section of a transistor. With emitter open, and collector reverse-biased as in normal operation, a leakage current flows called I_{co}.

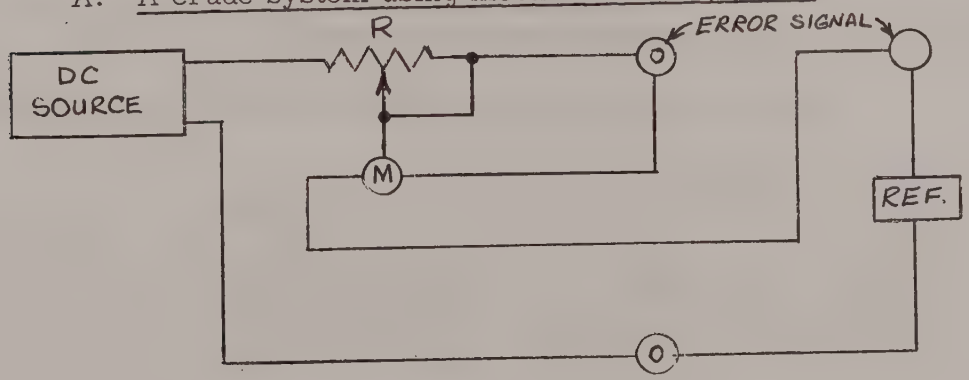
b.) The current path is through the base to the collector and back through the collector supply.

c.) The amount of I_{CO} flowing is extremely heat-sensitive, rising with increasing temperature. As the current increases, it causes increasing internal heat in the transistor which, in turn, causes more current to flow. If not checked, this leads to a condition of "thermal runaway" in which the transistor destroys itself.



II. Closed loop voltage regulators.

A. A crude system using mechanical components:



1. Operation of the system is as follows:

a. The DC supply furnishes a voltage higher than the output voltage desired.

b. The voltage drop across R reduces the output voltage to the desired value.

c. A motor, M, controls the position of the variable arm of the resistor, and hence the resistance.

d. The reference is a steady source of voltage equal to the output voltage desired.

e If the output voltage differs from the reference voltage, this error signal voltage appears across the motor and causes a chain of reactions to occur to restore the output voltage to the reference value.

f. The error signal voltage makes the motor adjust the resistor until the output voltage equals the reference voltage, at which time the error signal is zero and the motor stops moving.

2. The main drawbacks to the system are:

a. Slow response time.

b. Poor resolution of output setting.

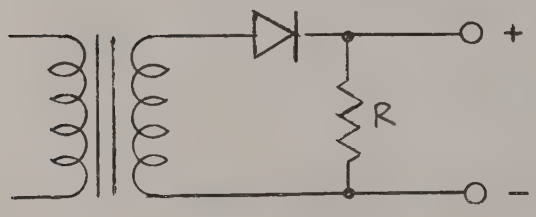
c. Moving parts may wear out.

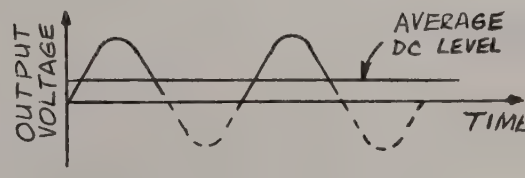
d. Output voltage not variably adjustable.

B. Substitution of Electronic Components in above System:

1. DC SOURCE. DC may be obtained with varying degrees of purity depending on the circuit and number of rectifiers used.

a. The half-wave rectifier is the simplest but most inefficient:

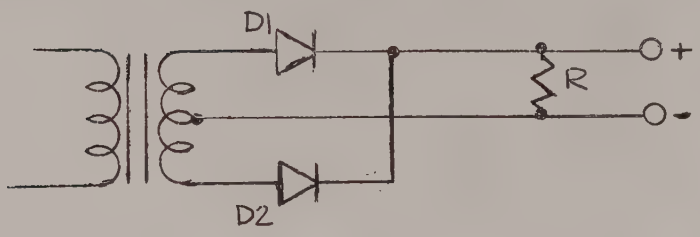


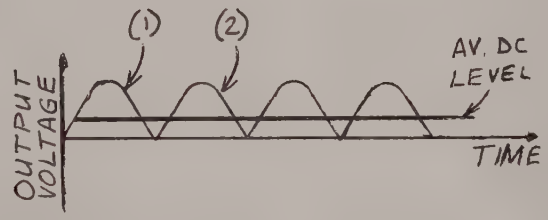


1.) Each time the upper terminal of the transformer becomes positive, the diode is forward biased and current flows through it and R , creating a pulse of output voltage across R . On the succeeding half-cycle, the polarity of the transformer secondary voltage is reversed and the diode, being now reverse-biased, does not conduct. Thus, during this half-cycle there is no output voltage.

The peak output voltage is high, but the average DC level is low.

b. The full-wave center-tap rectifier requires two diodes and a center-tapped transformer:



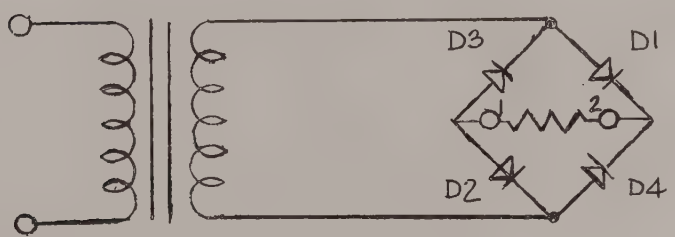


1.) Each time the upper terminal of the transformer becomes positive, D1 conducts and D2 does not. Thus current flows through D1 to the output terminals and causes the first pulse of output marked (1) in the waveform sketch.

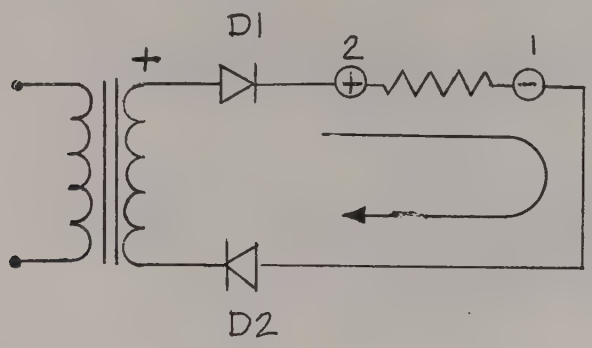
2.) During the succeeding half-cycle, the polarities are reversed so D2 conducts but D1 does not; however, D2 is connected to the same output point as D1, so this pulse of current appears at the output also, and is marked (2) in the waveform sketch.

3.) Note that now both half-cycles of the input voltage are being used and the DC level is therefore much greater.

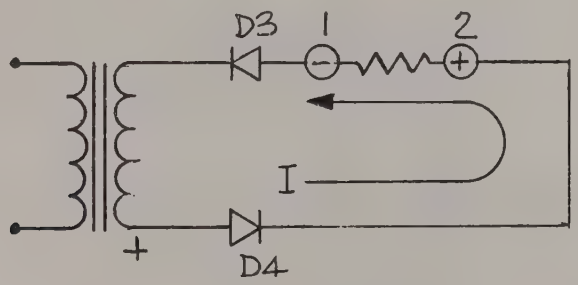
c. The Bridge Rectifier also uses both half-cycles of the input voltage and has an output waveform similar to the Full-wave Center Tap Rectifier. However, instead of using the Center Tap four diodes are required.



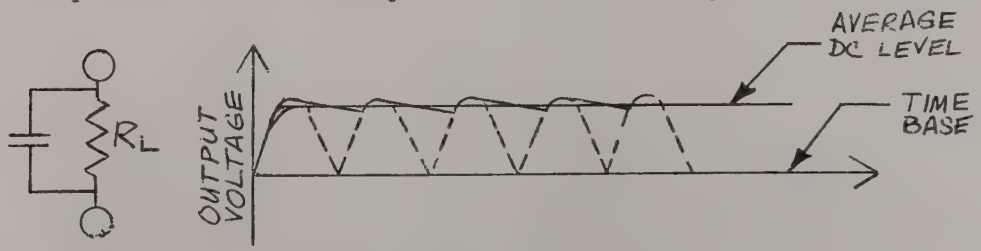
1.) When the upper transformer terminal is positive, the circuit looks like this:



2.) When the lower transformer terminal is positive, the symmetrically opposite diodes conduct and the effective circuit is like this:



d. Additional filtering or smoothing of the output waveshape is made possible by the addition of a capacitor across the output terminals. The capacitor tends to hold the voltage across it constant. Thus the deep gaps in the waveform are filled-in by the capacitor and the average DC level becomes greater.



Full Wave rectifier output voltage waveform after addition of Capacitor.

2. Reference Elements are stable voltages against which comparisons may be made to measure other voltages.

a. The simplest reference element is the battery. Most batteries are sensitive to atmospheric changes, temperature, age, and current drain. The Standard cell is a battery designed to maintain a precise constant voltage and serve as a standard voltage source. However, they too, are sensitive to environmental changes, shock, and position, and are expensive.

b. The VR tube is a two-element vacuum tube filled with an inert gas such as neon or argon. After a sufficient "firing voltage" has been applied to it, the VR tube has the ability to conduct variable amounts of current while maintaining a fairly constant voltage drop. This voltage regulating action is similar to that of the Zener diode.

c. The requirements and characteristics of Zener diodes (as discussed in Section IA) make them particularly suitable and compatible as reference elements in semiconductor power supplies.

3. Series Pass Transistors are used to control the amount of current passing through them. Their function in a closed-loop voltage regulator is analogous to the variable resistor which controls the current in the previously discussed mechanical regulator. (See Section II A.)

a. The series pass transistor must be driven by a signal of sufficient magnitude to control the current effectively. For this reason transistor amplifiers are required, and will be explained later.

b. Each transistor has voltage and dissipation limitations. In series pass transistor operation, if the supply is set for zero output voltage, the maximum voltage appears across the transistor. If the supply is set for maximum output voltage, very little voltage appears across the pass element. If both maximum current and zero output voltage are desired, the power dissipation in the pass elements is greatest.

4. Transistor Amplifiers

a. Why the need for amplification in a closed-loop regulator?

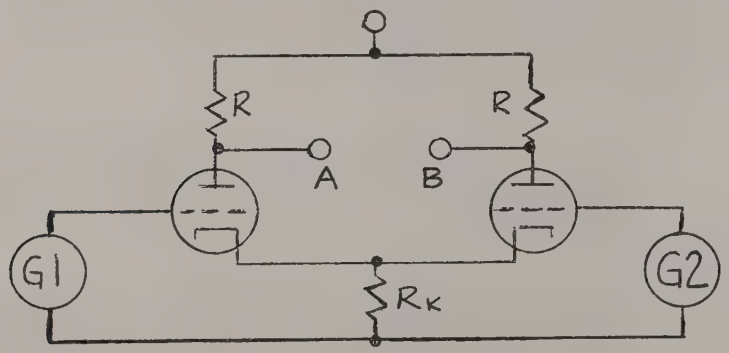
1.) In order to control the output within narrow limits, large gain is needed. The more gain, the more sensitive the control becomes.

2.) The Gain of the system depends on the number of amplifiers used and the gain of each. The current gain of a transistor is called its β (beta).

3.) If the pass transistor has a β (beta) of 50, a base current of 20 ma will control a collector current of 1 Ampere. If the amplifier driving this pass transistor has a beta of 50, the 20 ma will only need a base current control signal of $\frac{20}{50} = 0.4$ ma. The additional amplification stage therefore permits 0.4 ma of current to control 1 ampere of current flow in the pass element.

b. A comparison circuit compares a reference voltage with a sample of the output voltage. Any difference (error signal) that exists causes a proportional signal to be produced for controlling the series pass element.

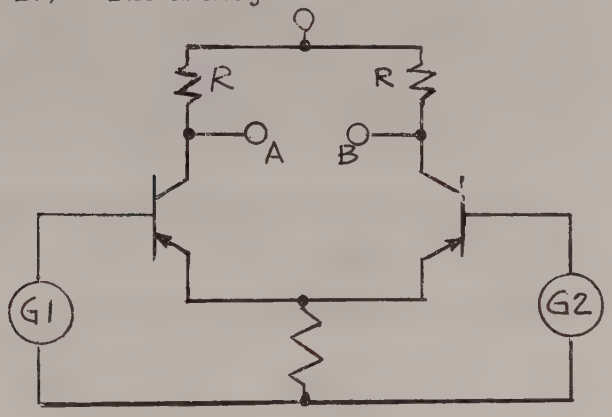
1.) In tube circuitry, a balanced amplifier design may be employed as a comparison device:



If G1 = G2, the two plate currents are equal: $V_{AB} = 0$.

If, however, G1 ≠ G2, the two plate current will be different, causing a voltage to appear across terminals A - B .

2.) The analogous transistor circuit is:



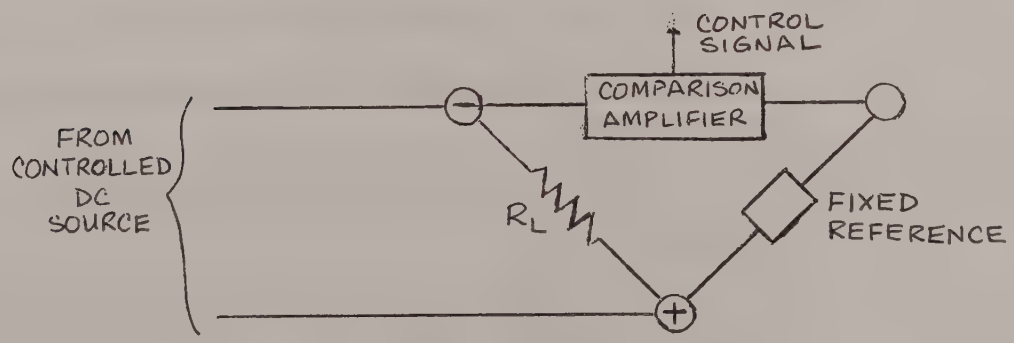
a.) Again, if the two inputs are equal, equal currents flow in the two collector resistors causing V_{AB} to be zero.

b.) If the two inputs are unequal, the transistors conduct differently causing the currents through the collector resistors to be different. This creates a voltage between terminals A - B which is proportional to the difference in input signals.

III. A practical semi-conductor designed voltage regulated power supply.

A. Development of bridge circuit.

1. Bridge for fixed output:



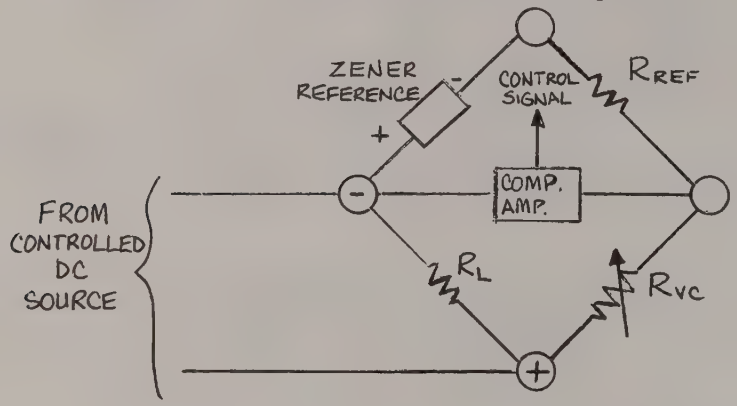
a. R_L is the load on the DC supply.

b. The Reference provides a constant voltage against which the output voltage of the supply is compared.

c. The comparison amplifier compares the supply's output voltage against the reference. If there is any difference (error signal), the balanced amplifier circuit initiates a control signal which causes the output voltage to be raised or lowered, as required, to the correct value.

d. One of the main disadvantages of this system is that the power supply output voltage is fixed at the value of the reference.

2. Bridge for variable output voltage:



a. The following is a more detailed consideration of the action of the bridge for a variable output power supply:

1.) During normal operation the bridge is balanced. As a result the voltage across the comparison amplifier is zero.

2.) The voltage across the Zener Reference is constant.

3.) The voltage across R_{ref} is the same as that across the Zener Reference.

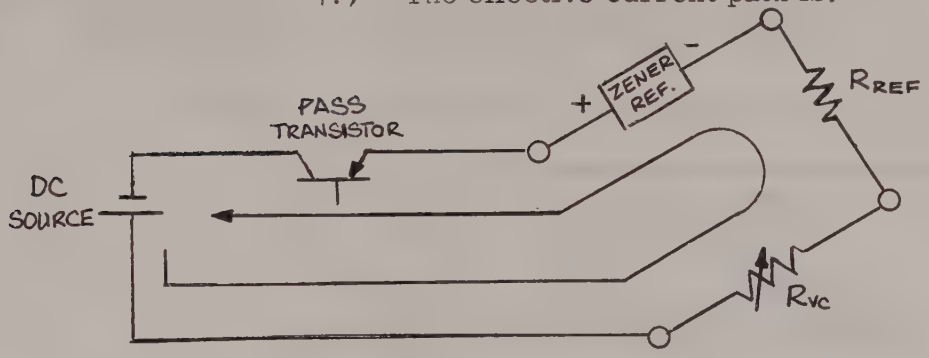
4.) Therefore the current through R_{ref} must be constant because both the voltage and resistance are fixed.

5.) Since the comparison amplifier is a high impedance device, no current flows through it. The only path left for this current to flow is through R_{VC} . Consequently, since the current is constant, the R_{VC} is constant, the voltage across R_{VC} is constant.

6.) By changing the value of resistance of R_{VC} , the voltage across it can be changed. Note that R_{VC} is in the same place

in this circuit as the Fixed Reference voltage was in the bridge for fixed output. R_{VC} now furnishes the reference voltage for the bridge circuit and the operation is the same as for the bridge for fixed output, but the disadvantage of that circuit has been overcome.

7.) The effective current path is:

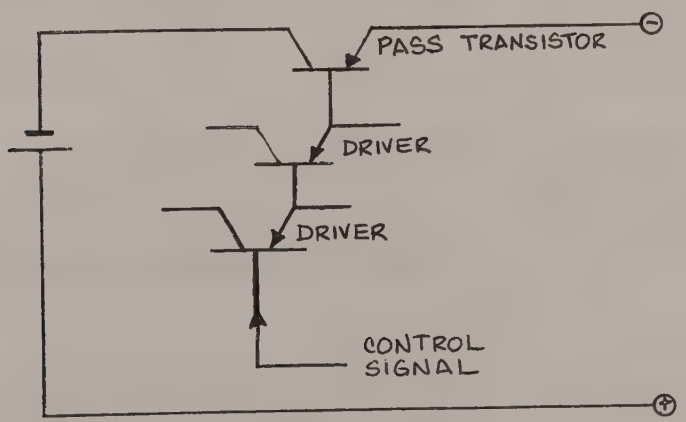


8.) Note that the component labelled "Zener Ref" is not only the Zener diode itself, but includes the complete reference supply required to make the Zener diode operate.

9.) If the output voltage tends to change from the required value, the bridge becomes momentarily unbalanced. The comparison amplifier senses this and initiates a control signal to the pass elements to raise or lower the output voltage. In this way the balanced condition is restored almost instantaneously.

B. Semiconductor circuit elements.

1. The control signal, as initiated by the comparison amplifier, must be fed into a series of amplifiers to control the pass elements.

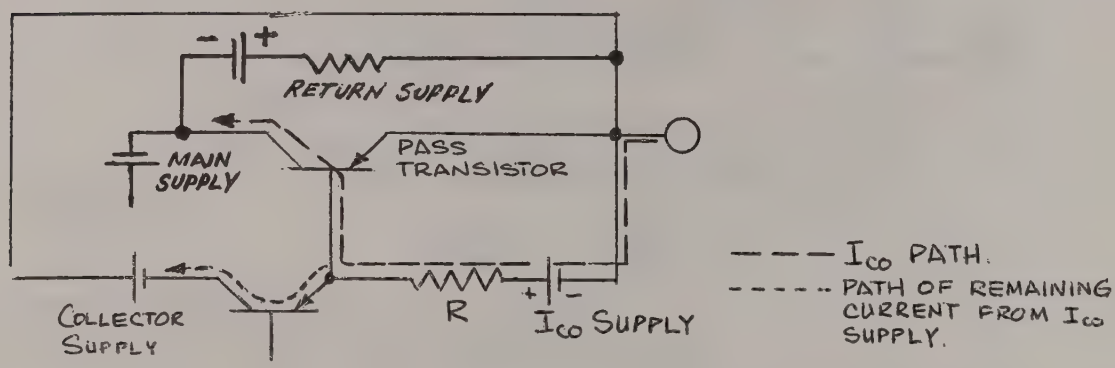


C. The auxiliary supplies.

1. I_{CO} supply.

a. The purpose of the I_{CO} supply is to positively "turn off" the transistor it is connected to, in the absence of a "turn on" control signal. It is somewhat like the "C" bias supply of a vacuum tube and must provide sufficient current to turn off the transistor under the worst conditions of voltage and heat.

b. The following circuit shows how it is connected.



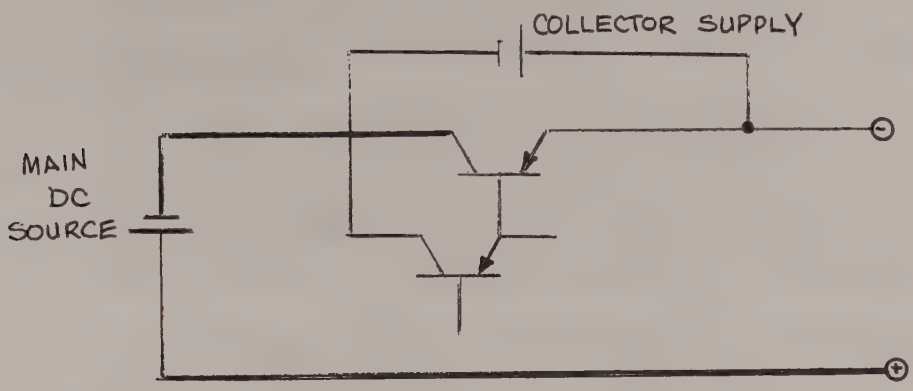
c. Because of the small value of R and the normally small I_{CO} the I_{CO} supply voltage appears effectively across the base-emitter junction, turning the transistor off. If a turn-on signal is received, the previous amplifier stage begins to conduct, pulling additional current through R from the I_{CO} supply. This lowers the base bias voltage because of the added drop through R and results in the pass transistor turning on. *

2. Collector supply.

a. Collector voltage is required for operation of a transistor. While in power supplies, the pass elements do have a collector voltage source (the main DC source) it is usually desirable to provide a separate source for drivers and amplifiers to permit these stages to be designed for lower power transistors.

* Remark: A simple rule of thumb will prove helpful to those not accustomed to working with transistors. Provided collector voltage is present, if the polarity of the base-emitter bias is such as to make current flow in the direction of the arrow, the transistor will conduct. If it tends to make current flow opposite to the direction of the arrow, the transistor will cut off, or not conduct.

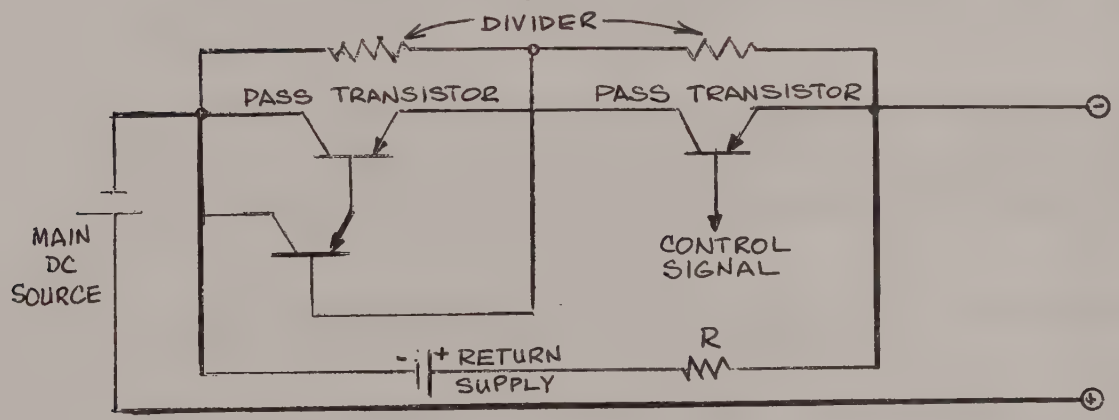
b. A typical collector supply connection:



3. Return supply.

a. The return supply is used to enable the output voltage to be set to zero volts by bucking out circulating current in the main DC path.

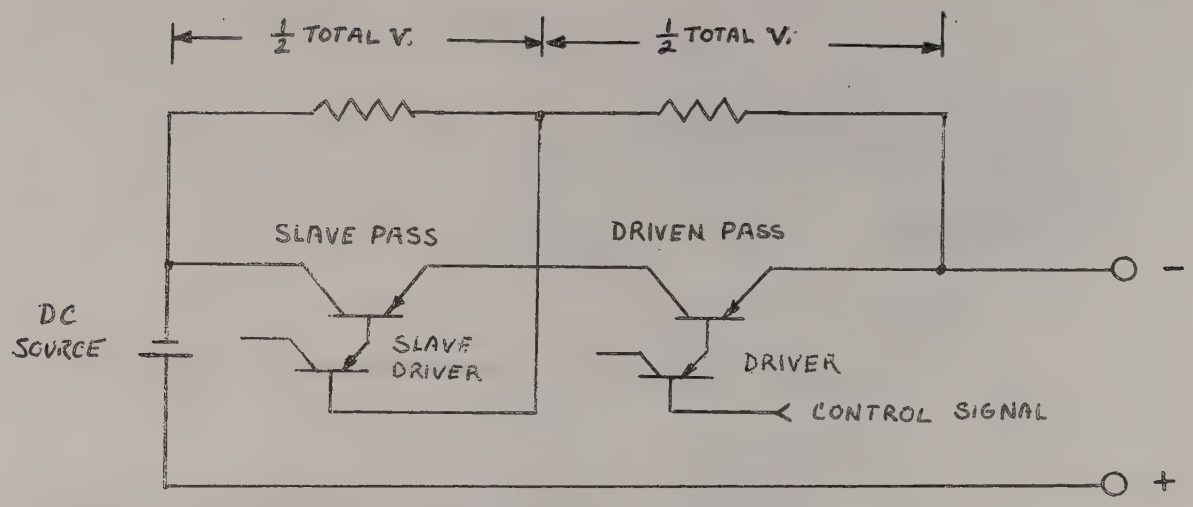
b. For example, in high voltage power supplies transistor pass elements must be connected in series. A voltage divider makes the bias of the additional series transistors follow the bias of the "directly driven" pass element.



c. If the pass transistors receive a signal to cut off completely, they will. However, current still flows through the divider network, creating a small voltage at the output. This action provides a "minimum operating" current for the pass transistors which prevents a loss of sensitivity to the error signal.

IV. A complete Kepco power supply.

A. On the schematics, the major circuits discussed previously are labelled. However, the bridge circuit appears partly on the power unit schematic and partly on the control unit schematic. Standard nomenclature is used, and the circuit may be traced using the



THE SLAVE PASS

simplified bridge circuit on page 13 as a guide.

B. The Slave Pass.

1. On high voltage supplies, the voltages appearing across the pass transistors may exceed the voltage limitations of the transistors. To enable high voltage operation, transistors may be connected in series so the drop across each one individually is less, in the same manner that capacitors may be placed in series for high voltage operation.

2. In order to force the voltage division to be equal across the series transistors, a resistor bleeder-divider is connected across them. The voltage at the midpoint is half of the total voltage. Assuming there are only two transistors in series, this midpoint voltage is applied to the base of one of the drivers of the "slave pass". Whatever the total voltage across the bleeder; the slave pass will have half that voltage across it, while the "driven" pass will have the other half.

C. Input control circuit.

1. Because transistors are easily destroyed by excessive heat either from external sources or internal sources, a thermostat is attached to one of the pass transistors and connected to the input control circuit in order to shut down the supply in case of too great a temperature rise.

2. When the supply is turned off, the regulator stops operating but the input capacitor is still charged. This may result in an upward voltage spike in the output at the instant of turn-off. To prevent this, the relay has an additional set of contacts that discharges the input capacitor upon turn-off.

3. Since the toggle switch controls the relay only, no heavy current passes through it and it may be of light construction.

4. The circuit is fail-safe; that is, if any component fails, the set will shut down.

5. Operation of the circuit is as follows:

a. When the switch is closed, voltage is applied across the series circuit consisting of a diode, capacitor, and relay coil. The initial pulse charges the capacitor and energizes the relay.

b. Once the relay has been energized, a set of contacts provide a new current path to hold it in this position as long as the relay is energized. This current path is in series with the thermostat, and if the thermostat is open, the relay will not hold, and the supply cannot remain "on."

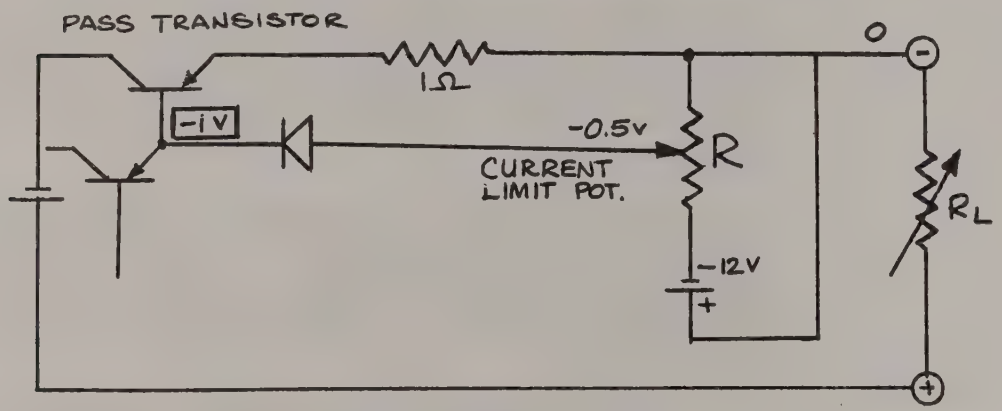
c. To reset after the thermostat has closed again, it is necessary to provide another pulse of input current by turning the switch "off", then "on" again.

D. Current limit circuit.

1. The purpose of this circuit is to limit the maximum current that can be drawn from the supply to a safe value, even if the output is shorted.

2. Operation of the circuit is as follows:

Assume in the following circuit that R is adjusted to enable the circuit to limit at some value of current.



a. As R_L is adjusted so that more load current flows, more current also flows through a 1 ohm series resistor (or equivalent equalizing resistors). This makes the emitter of the pass transistor more negative with respect to the "−" output terminal.

b. The base voltage of the transistor must follow the emitter within a fraction of a volt.

c. When the base voltage reaches a point where it is more negative than the position of the arm on resistor R, the diode will conduct, clamping the base of the pass transistor to the fixed voltage of the resistor arm.

d. This tends to make the pass transistor base positive with respect to the emitter, (reverse biased since this is a PNP type), and the current flow through it is abruptly limited.

e. A reduction in load current causes less drop across the 1 ohm resistor, making the base more negative again, and permitting more current to flow until equilibrium is reached.

f. When the clamping action takes place, the voltage is fixed and completely "swamps" the control signal.

ADJUSTMENTS:

1. Voltage Control: Enables the output voltage to be adjusted throughout range of the supply.

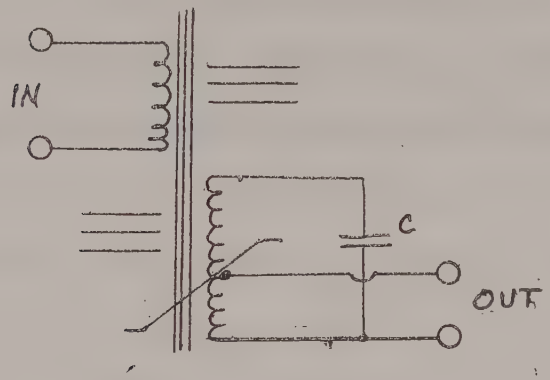
2. Maximum Current Control: Set at factory so that the maximum current cannot exceed approximately 120% of the maximum rated current of the supply. This permits the supply to operate continuously into a short circuit without overheating or damage.

3. Current Limit Control: May be screwdriver adjusted to permit current limiting at values under 120% of the maximum rated current. This permits the customer to protect his circuits by adjusting the current limiting to the exact value he needs. The usual range of adjustment of this control is from 10% to 120% of the supply ratings.

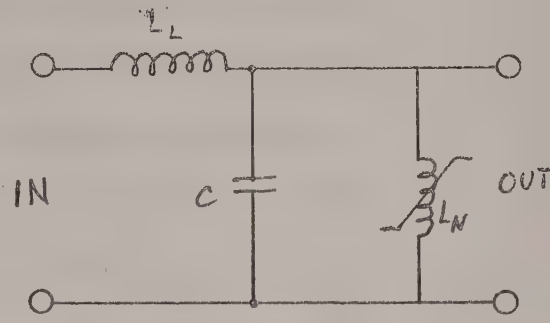
The following material has been collected to illustrate the operation of various specific circuits in Kepco Power Supplies. This material is intended to supplement the generalized discussion of the preceding section and to acquaint technicians with the operational characteristics of the various sub-circuits in a Kepco Power Supply.

Not all of the various sub-circuits are contained in any given Power Supply. Their various combinations comprise the several Power Supply design groups presently available from Kepco. A Power Supply's own Instruction-Service Manual will detail the circuit layout for any given unit.

....FLUX-O-TRAN or FLUX-OSCILLATOR is a line regulating power transformer, that prevents output voltage variations with line voltage variations and simultaneously offers short circuit protection.



SCHEMATIC REPRESENTATION OF FLUX OSCILLATOR



EQUIVALENT DIAGRAM

The magnetic shunt shown in the schematic circuit is represented by a linear inductance in series with the line voltage and is labeled L_L. The secondary winding of the FLUX OSCILLATOR is represented by a saturable reactor labeled L_N whose reactance is very high while in an unsaturated state, and in this instance can be assumed to be a short circuit. Capacitor C is in series with the linear inductor L_L and the series L_L C circuit resonates at line frequency. The voltage across C is very large, because the current in the resonant circuit is large and the voltage across C is the product of the current in the capacitor and the reactance of the capacitor. As the voltage increases across C, the voltage increases across L_N also. L_N saturates, its inductance becomes the residual inductance, which is very small, its reactance becomes practically zero and it acts as a short circuit across capacitor C. The capacitor discharges through the saturable inductor and builds up a magnetic field around L_N. When C

is completely discharged the collapsing magnetic field around L_N tends to continue the current in the same direction that it was flowing before. The capacitor C gets charged in the reverse direction by the current that is induced by the collapsing magnetic field. The same cycle repeats in the opposite direction also and the circuit behaves as an OSCILLATOR. If the transition from nonsaturated into saturated state is rapid, as can be approximated in actual practice, the voltage waveform across capacitor C is nearly square wave. This means that the saturable inductor L_N is always saturated during the capacitor discharge time.

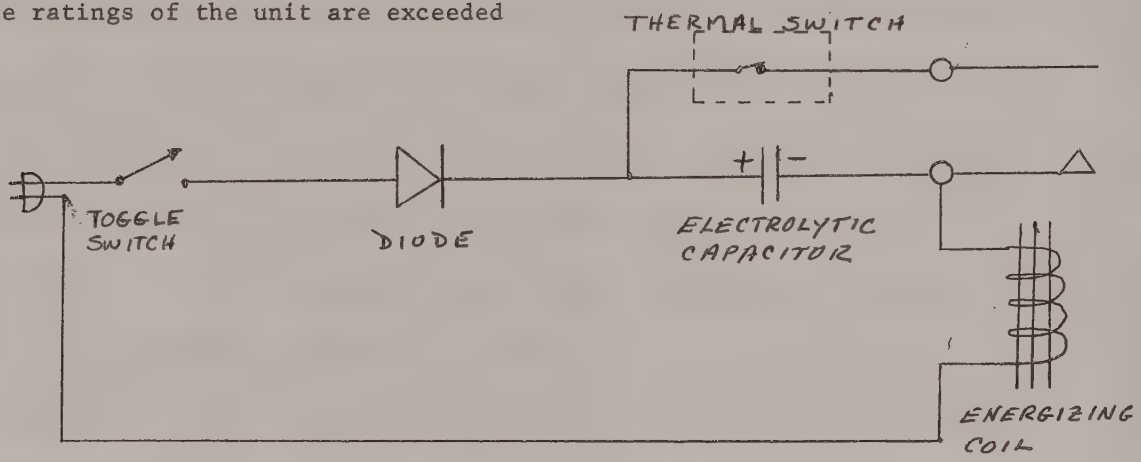
Whenever a transformer is saturated, the secondary voltage will increase only by a small amount for an increase in the primary voltage, because the number of flux lines linking the primary to the secondary will not increase. Actually the secondary voltage will increase slightly, but this increase can be bucked out by using a compensating winding. (Not shown in schematic.) FLUX-O-TRANS are designed so that the secondary winding saturates at the lowest usable line voltage, therefore for an increase of line voltage the output voltage of the FLUX OSCILLATOR will not increase.

The purpose of the secondary tap is to reduce the output voltage of the FLUX OSCILLATOR to as low a value as needed and also to enable the designer to use a smaller value of capacitance, since the capacitance reflected into the primary circuit is multiplied by the square of the turns ratio.

Whenever the output of the FLUX OSCILLATOR is short circuited, the equivalent circuit modifies to a linear inductance in series with the output current. In this manner the output current is limited to a certain maximum value which cannot be exceeded, because the output voltage decreases in order to check the current flow.

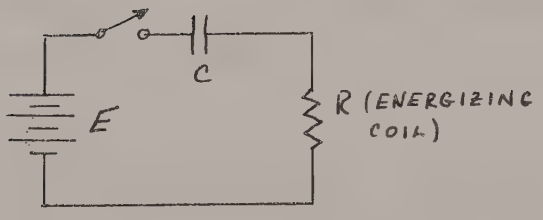
INPUT CONTROL CIRCUIT

The INPUT CONTROL CIRCUIT is the "ON-OFF" control for the Power Supply. It is activated either by an "ON-OFF" toggle switch or by the normally closed thermal switch, which turns the supply off by opening the relay in case the maximum temperature ratings of the unit are exceeded

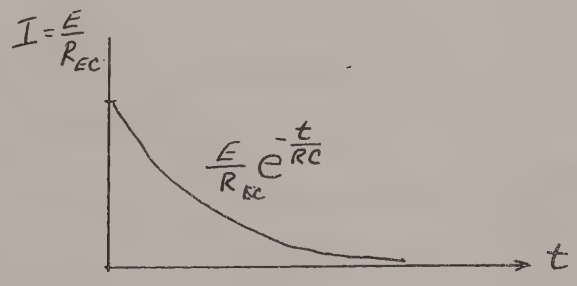


Simplified Input Control Circuit

The basic INPUT CONTROL CIRCUIT before the relay is "pulled in" can be represented by a simple equivalent circuit shown below.



Equivalent input control circuit



Charging current of capacitor

When the toggle switch is closed initially, a current surge flows through the circuit. This current surge, which is the charging current of the large capacitor, momentarily "pulls in" the relay and closes the contacts. The normally closed thermal switch is connected to one of the contacts in such a way that when the relay contacts close the capacitor is short circuited and the relay stays "pulled in". Other contacts on the relay connect the power transformers to the power line and protect the unit from over voltage surges

The thermal switch is located near the PASS CIRCUITRY where normally most of the power is dissipated and the highest temperatures in the unit prevail. If the temperature near the thermal switch exceeds the rated temperature of the Power Supply the normally closed thermal switch opens. The current through the relay coil is interrupted because the capacitor in series with the energizing coil "blocks" the rectified A.C. current All the contacts open and the line power is disconnected from the unit To pull the relay in again the toggle switch has to be opened and closed again to get the surge through the capacitor and energizing coil. If the unit has not cooled off sufficiently, the thermal switch will be open and the relay will not stay "pulled in". More time will have to be allowed for the Power Supply to cool off.

The main advantage of the INPUT CONTROL CIRCUIT is that heavy currents can be controlled by a toggle switch or by a thermal switch, which are not able to carry heavy currents.

MAXIMUM CURRENT ADJUST.

The Maximum Current Adjust is a factory-set adjustment intended to set the maximum amount of DC current that can be drawn from the Supply at short circuit. It serves to protect both the load circuit and the pass transistors in the Power Supply from being subjected to unnecessary excessive current due to external overloading.

Limiting is accomplished by making transistor Q4, (see Fig. 1) the Amplifier/Clamp, go into saturation when the Supply attempts to deliver more current than the pre-set maximum. As it goes into saturation it limits the increase in negative voltage at its collector, thus limiting the increase in negative voltage at the base of the pass element pre-driver Q3, that is required to cause the pass elements to deliver more current to the output. At full short-circuit, theoretically, the error signal will attempt to drive the base input of the pass elements more and more negative, to deliver unlimited short-circuit current. However, the fixed negative bias on the emitter of Q4 derived from the adjustable arm of the control and the -9 volt supply, sets the operating and the saturating level of transistor Q4. In saturation the collector approaches being nearly equal to, but can never be more negative than the emitter.

Since limiting action overrides and reduces the feedback control in the closed loop system, it degrades regulation and ripple accordingly. To allow an operating margin before limiting begins, the Maximum Current Adjust is usually set for a maximum current at short-circuit, equivalent to approximately 125% above the normal rated maximum current for the Supply. This allows for adequate protection at full short-circuit, while providing for limiting not to begin until just past normal maximum current, so that it can be operated at maximum current without degrading regulation or ripple.

CURRENT LIMIT ADJUST.

The Current Limit Adjust allows the value of maximum current at short-circuit to be varied over a range from the maximum value, as set by the Maximum Current Adjust, down to 10% of the rated maximum output current of the Supply. It is provided as a separate control so that the short-circuit current limiting can be readily varied without having to disturb the setting of the Maximum Current Adjust.

The voltage on the base of the Pass transistor, Q1 (See Fig. 1) is negative (PNP) with respect to its emitter. Also, it closely follows the voltage on the emitter within a fraction of a volt, typically on the order of 0.25 volt at no-load. The voltage on the emitter is negative with respect to the negative regulated output terminal, and proportional to output current due to the drop across the small re-

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sistor R. Similarly, the bases of the driver (Q2) and pre-driver (Q3) are each negative with respect to their emitters, (PNP) and follow their emitter voltages within a fraction of a volt. The combined result is that the base of the pre-driver is negative with respect to the negative output terminal, and varies with output current nearly in direct proportion to the drop across R. For an increase in output current, the base of Q3 must become more negative; and conversely, for a decrease in current the base becomes less negative. Output current limiting is accomplished by limiting the negative bias at the base of the pre-driver transistor (Q3) to an adjustable fixed value derived from the Current Limit Adjust control. This voltage is applied to the base of Q3 through the diode CR so that when the output current is below the value where limiting is to begin, the signal at the base of Q3 is less negative than the negative voltage that is on the anode of CR. In this condition the diode is reverse biased, or cut off, and Q3 is isolated from the limiting voltage from the control. When the Supply attempts to deliver current to the output above a certain level, the voltage on the base of the pre-driver Q3 will become sufficiently negative to forward bias the diode causing it to conduct. Except for the small drop across the diode, the voltage at the base of Q3 is then fixed and limited to the negative voltage from the control and cannot go more negative, thereby limiting the current through the pass elements.

As in the case of the Maximum Current Adjust, the Current Limit Adjust is set on the basis of short-circuit current; but limiting will actually begin to take place at some constant increment of current below the value of short-circuit current for which it is set. Unless otherwise indicated, this increment is usually equal to approximately 25% of the rated maximum current of the Supply. In setting the Current Limit Adjust, it should be set to a short-circuit value that is greater than the operating current by at least the amount of this increment.

For example, in a Model SC 18-2, the rated maximum current is 2 amperes, and the limiting increment is .5 amperes. If the output were going to be operated at 750 ma, the short circuit current could be set to as low as 1.25 amperes. Limiting would begin (and regulation would begin to be degraded) at current just past 750 ma; at short-circuit it would be a maximum of 1.25 amperes.

One important consideration that should be remembered when using a current limiting function on a voltage regulated power supply is that when the load is in the range where limiting action is taking place, regulation and the constant voltage characteristic is degraded. Since current (I) can no longer increase, as load resistance (R) decreases, output voltage (E) must decrease accordingly; (E=I x R). This is pointed out because it is easily overlooked, and often accounts for complaints of "low voltage", "loss of regulation", "high ripple", etc., from users of this type of Power Supply.

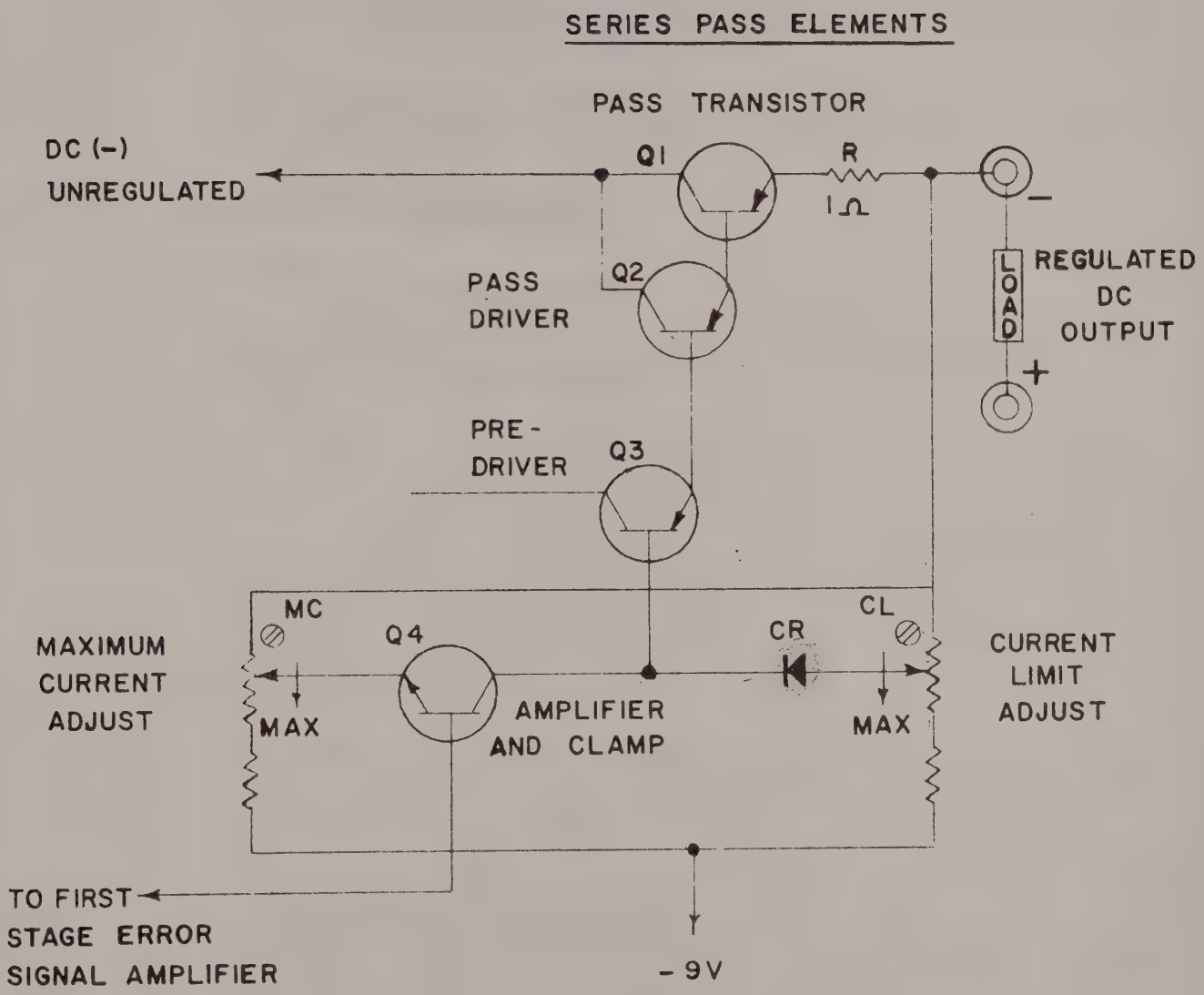

Fig. 1 Simplified Circuit Diagram - Current Limiting Circuits, SC Series Power Supplies.

INSTRUCTION MANUAL

VOLTAGE REGULATED POWER SUPPLY

MODELS SM 160-1
AND SM 160-1M

SERIAL NO. .....

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SECTION B

BRIEF THEORY:

Two circuit schematic drawings titled "POWER UNIT" and "CONTROL UNIT" are included in the Reference Index of this instruction manual. These drawings contain designations corresponding to the capitalized terms in the following discussion.

Some basic functional relationships in this power supply are illustrated in block Diagram B-1 (Page B-2A).

The POWER UNIT includes:

DC SOURCES:

....MAIN SUPPLY - (consisting of a Kepco "Flux-O-Tran" transformer, full wave bridge rectifier, and capacitive filter) provides line regulated DC power for the output, via the PASS CIRCUITRY.

....AUXILIARY SUPPLIES: COLLECTOR SUPPLY (negative full wave rectified) for PASS CIRCUITRY driver stages not connected to MAIN SUPPLY; I_{CO} SUPPLY (full wave rectified) compensates for spurious biasing effects of collector leakage current; RETURN SUPPLY (full wave rectified) acts as leakage current path for series pass transistors and as bleed path to provide minimum operating current for pass transistors; CONTROL UNIT SUPPLY (full wave rectified).

PASS CIRCUITRY:

The power transistors which function as pass elements (i.e. are in series with the load) may be regarded effectively as variable resistors (or conductors) controlled by a CONTROL SIGNAL. The current "passed" by these elements is a function of the emitter-base bias. The CONTROL SIGNAL is applied to the base terminal; hence a negative CONTROL SIGNAL will aid the forward conduction of a PNP transistor while a positive CONTROL SIGNAL will reduce the forward conduction. In response to the CONTROL SIGNAL the pass elements effect a current and voltage distribution in the main DC loop which holds the output voltage constant.

The CONTROL UNIT includes:

REFERENCE CIRCUITRY:

The function of the REFERENCE CIRCUITRY is to maintain a precise, stable, voltage standard for the COMPARISON AMPLIFIER.

COMPARISON AMPLIFIER:

The COMPARISON AMPLIFIER is essentially a series of cascaded transistor amplifiers which boost the differential error signal produced in the COMPARISON BRIDGE to a level sufficient to drive the PASS CIRCUITRY. The COMPARISON AMPLIFIER is connected across the COMPARISON BRIDGE from the junction of the VOLTAGE CONTROL and the REFERENCE RESISTANCE to the junction of the REFERENCE DIODE and the negative output terminal (See Diagram on Page B-2A). This arrangement is similar to that of a null galvanometer across a Wheatstone bridge. Unbalance in the COMPARISON BRIDGE is amplified to produce a CONTROL SIGNAL of suitable magnitude and phase to effect corrective action by the PASS CIRCUITRY.

COMPARISON BRIDGE: (See Diagram B-2, Page B-2A).

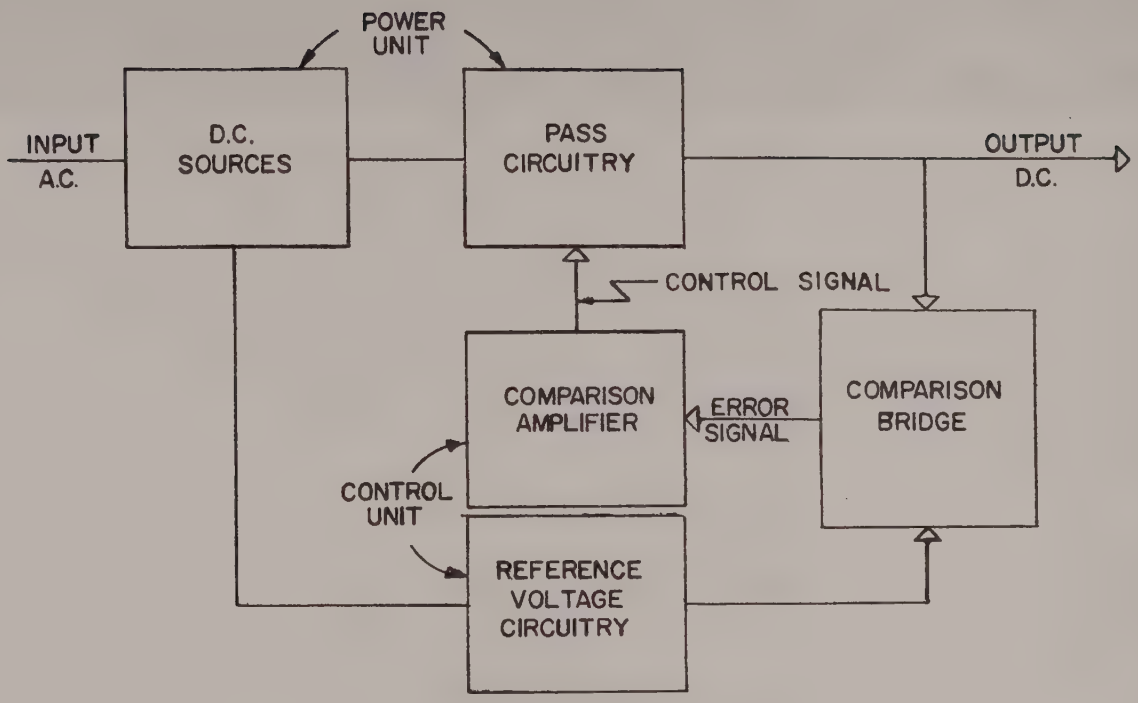
This bridge circuit implements the comparison between the OUTPUT VOLTAGE and the REFERENCE VOLTAGE. The signal produced by the comparison drives the COMPARISON AMPLIFIER.

Balance occurs in the Comparison Bridge when the following ratios are equal:

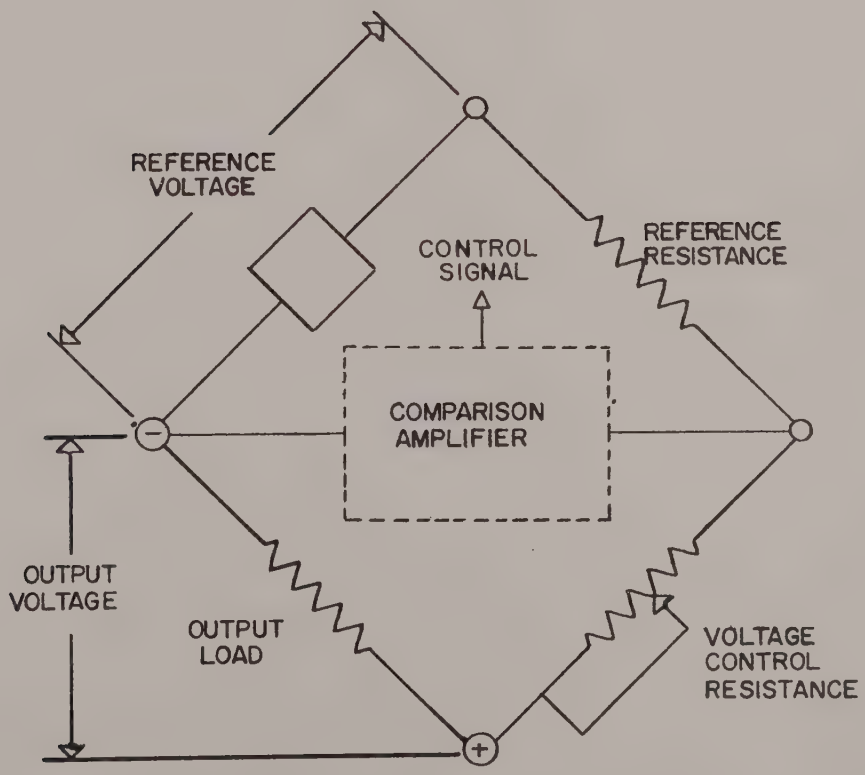
$$\frac{\text{Output Voltage}}{\text{Voltage Control Resistance}} = \frac{\text{Reference Voltage}}{\text{Reference Resistance}}$$

When, for example, the Comparison Bridge is unbalance by a decreasing output voltage drop across the load, it gives rise to a negative signal at the base of the COMPARISON FOLLOWER in the COMPARISON AMPLIFIER circuit. This signal is amplified in cascade and communicated to the pass elements as a negative base input aiding their forward conduction and consequently increasing the output voltage.

A bridge unbalance caused by an increasing output voltage produces, of course, a chain of oppositely biased circuit responses which reduce the voltage across the load.



(DIAGRAM B-1) *VOLTAGE REGULATED POWER SUPPLY*



(DIAGRAM B-2) *COMPARISON BRIDGE*

INSTRUCTION MANUAL

DC POWER SUPPLY

MODEL SC 36-2, -2M

SERIAL NO. .....

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SECTION B.

THEORY OF OPERATION

This power supply is of a servo or closed loop design in which the pass elements are in series with the load. (See block diagram B-1).

The voltage drops in the closed loop system are automatically adjusted according to the comparison of a sample output voltage with the reference voltage in the CONTROL UNIT. The differential product of this comparison is amplified and fed back as the ERROR INPUT to control the voltage drop across the pass transistors. The ERROR INPUT to the PASS CIRCUITRY is a negative or degenerative feedback signal. Consequently, the voltage drop across the pass transistors is such as to oppose output voltage change.

CAPITALIZED TERMS ADOPTED FOR FOLLOWING OUTLINE AND DISCUSSION REFER TO DESIGNATIONS ON THE CIRCUIT SCHEMATICS IN THE REFERENCE INDEX.

.....1. POWER UNIT (Circuit Schematic Tile)

A. INPUT CONTROL CIRCUITRY - Controls power input from the line to the DC SOURCES.

B. DC SOURCES - Provide main and auxiliary rectified power for all DC circuitry.

C. PASS CIRCUITRY - In the MAIN DC path to the output. All current drawn by the load goes through the pass elements, hence the name.

.....II. CONTROL UNIT (Circuit Schematic Tile)

A. REFERENCE VOLTAGE CIRCUITRY - Maintains a stable voltage standard for the comparison circuitry.

B. THE COMPARISON AMPLIFIER - Functions as the "error sensing" and cascade amplification circuit.

.....III. COMPARISON BRIDGE -

Consists of elements in both the POWER UNIT and CONTROL UNIT in a circuit configuration which effects a comparison between an output voltage sample and a stable reference voltage.

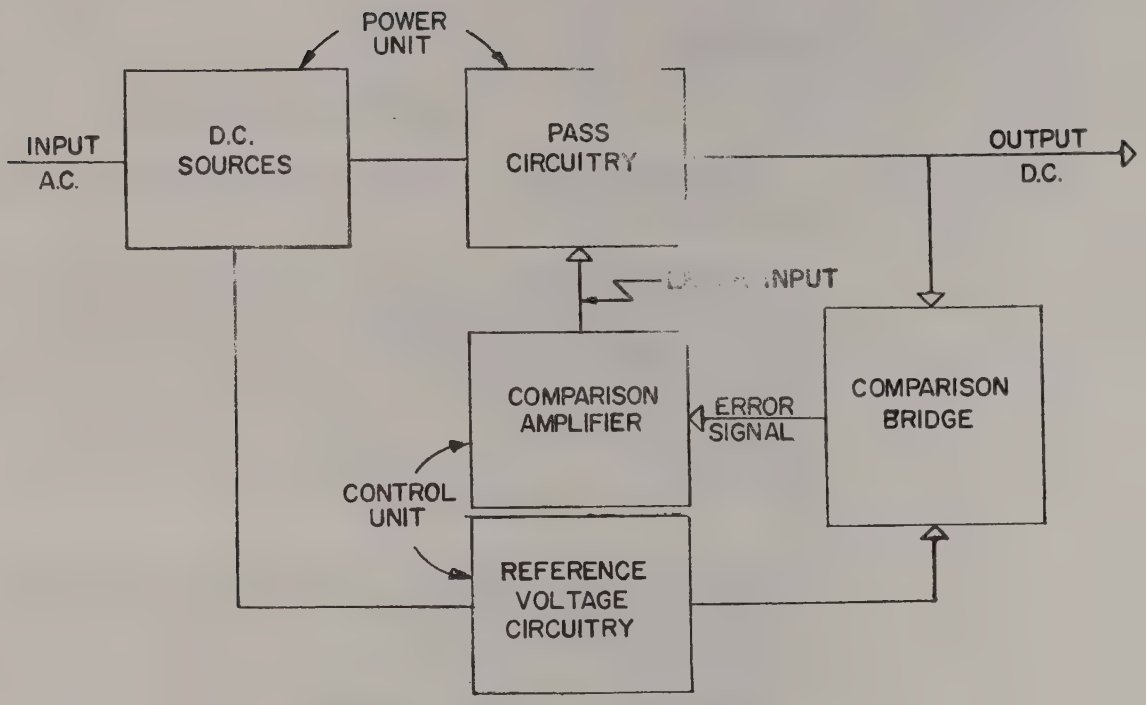


DIAGRAM B-1

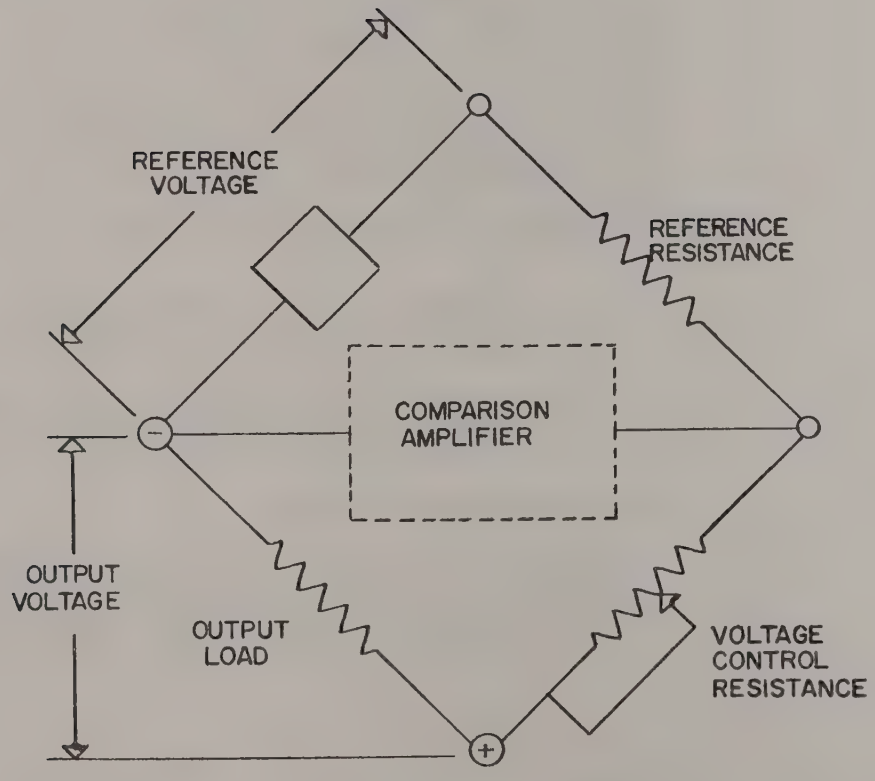


DIAGRAM B-2

NOTE:

The following discussion describes the elements of the foregoing outline in greater detail. As before, capitalized terms refer to designations on the schematic diagrams. Some of this discussion is of a general nature and may not apply in every detail to this specific model. Variations in the basic outline occur primarily in connection with the PASS CIRCUITRY INPUT CONTROL CIRCUITRY or the REFERENCE VOLTAGE CIRCUITRY and reflect design considerations relevant to the particular output requirements of the model. It should not be assumed that a set of circuit schematics is incomplete because it does not include all of the reference nomenclature used in this discussion.

.....I. POWER UNIT

A. INPUT CONTROL CIRCUIT:

(1) With the input switch closed, a forward bias on one semiconductor diode in the ENERGIZING CIRCUIT will draw a charging current for the capacitor which energizes the INPUT RELAY coil closing the input to the DC SOURCES transformers. As soon as the INPUT RELAY is closed, the DC in the input control circuit circulates through the thermal relay and input relay coil, bypassing the charged capacitor and holding the relay closed.

(2) If the pass element containing the thermostat control becomes overheated, the thermal switch opens the DC path to the INPUT RELAY de-energizing the relay coil and cutting off the input to the DC SOURCES.

NOTE:

The AC line power must be interrupted in order to reset the input relay after the thermal switch has opened the input to the DC SOURCES. Once the capacitor in the ENERGIZING CIRCUIT is charged, it cannot hold the relay when the thermal switch opens. This action tends to prevent damage to the pass elements from overheating in case the transistor associated with the thermostat dissipates heat faster than the other pass elements.

(3) When the input relay is opened by the action of the thermal switch or by pulling the line cord, the DISCHARGE RESISTOR effectively shorts the MAIN FILTER CAPACITOR preventing overvoltage surges.

NOTE:

For Models SC 18-4, SC 36-2 and SC 3672-1 substitute the following paragraph for section I-A.

These models employ a slightly different turn-on circuit - refer to schematic diagram.

....I. POWER INPUT

A. INPUT CONTROL CIRCUIT:

(1) INPUT RELAY automatically interrupts the power input to the DC SOURCES whenever the thermostat control detects overheating in the PASS CIRCUITRY. When it is thrown in response to an over-temperature condition, it provides a discharge path for the MAIN FILTER capacitor.

(2) OVERVOLTAGE RELAY provides a discharge path for the MAIN FILTER capacitor whenever the line input is interrupted.

(3) DISCHARGE RESISTOR - When the input to the DC SOURCES is opened by interrupted line power or the action of the thermostat control, the DISCHARGE RESISTOR effectively shorts the MAIN FILTER capacitor. This prevents overvoltage surges.

B. DC SOURCES:

(1) RETURN SUPPLY (full wave rectified and filtered) - provides a return path for leakage current (I_{CO}) from the pass transistors.

It is also a bleed path which provides a minimum operating current for the emitters of the pass transistors, enabling them to continue to remain operative or "sensitive" to the ERROR INPUT when the load current becomes zero or vanishingly small.

(2) MAIN SUPPLY (full wave rectified and filtered) - provides MAIN DC for the output, subject to the regulatory action of the PASS CIRCUITRY. The MAIN DC path includes the pass elements and the load in series.

(3) I_{CO} SUPPLY (full wave rectified) - Provides a supply of current to prevent spurious biasing of the pass transistors by collector leakage current (I_{CO}). I_{CO} generated as a function of temperature and flowing oppositely to the emitter base current tends to alter the ERROR INPUT unless this compensating supply provides bias stabilization.

(4) COLLECTOR SUPPLIES (negative half-cycle rectified) - provide proper collector bias for the PRE-DRIVERS.

C. PASS CIRCUITRY:

The power transistors which function as pass elements may be regarded as electronic variable resistors (or variable conductors) controlled or "varied" by an amplified ERROR INPUT. The amount of current "passed" by these transistors is a function of the magnitude of the forward conducting emitter-base bias. Since the ERROR INPUT is applied to the base terminal, a negative input will aid the forward conducting bias of a PNP transistor while a positive input will reduce the forward conducting bias. In response to the polarity and magnitude of the ERROR INPUT, the pass transistors control the current and voltage distribution in the MAIN DC loop and effect a constant output voltage.

Two main classifications of pass transistors may be indicated on the schematic acoording to the way in which they are driven:

(1) DRIVEN PASS - "driven" by the ERROR INPUT from the CONTROL UNIT. A DRIVER and a PRE-DRIVER may be connected in cascade with the DRIVEN PASS. These amplification stages increase the response and sensitivity of the system to output voltage changes. The DRIVEN PASS may be a single series pass transistor

or a series pass group of transistors connected in parallel for increased current capacity.

(2) SLAVE PASS - found in transistorized units requiring more than one series pass group in the MAIN DC path. These pass transistors "slavishly" follow the response of the DRIVEN PASS to the ERROR INPUT. The SLAVE PASSES are driven through a SLAVE VOLTAGE DIVIDER which effects an approximately equal voltage division among the series pass groups in models where the voltage range requires more than one group of series pass elements. The SLAVE PASSES may or may not have preliminary amplification stages in cascade.

When series pass groups contain transistors connected in pparallel, an EQUALIZING RESISTOR is associated with each transistor. These EQUALIZING RESISTORS, tied to each emitter, provide a means of compensation for intrinsic differences among transistors within a pass group.

The expression "drop voltage" is sometimes used to describe the amount of voltage drop required of the pass elements to bring the COMPARISON BRIDGE into balance. This is the difference between the input and the desired output. True balance or stability is inherently impossible in a servo system, but the unbalance may be reduced to as small a magnitude as desired in a dynamically corrective system.

II. CONTROL UNIT

A. REFERENCE VOLTAGE CIRCUITRY:

The function of the REFERENCE VOLTAGE CIRCUITRY is to maintain a precise, stable voltage for the COMPARISON BRIDGE. This is normally achieved according to the model CONTROL UNIT with either of two basic design approaches:

(1) A CASCADE ZENER REFERENCE, consisting of Zener diodes of successively decreasing values in cascaded stages each of which produce an increasingly regulated reference voltage. In practice, usually only two stages are used so that in effect the first Zener diode is a regulator for a voltage reference diode.

(2) Balanced amplifier regulation - Any disparity between the bases of the transistors in the set of 1st BALANCED AMPLIFIERS is coupled to the set of 2nd BALANCED AMPLIFIERS. The 2nd BALANCED AMPLIFIERS couple this amplified "error signal" to a REFERENCE DRIVER and a REFERENCE PASS which regulate the current through a REFERENCE DIODE in a manner analogous to the action of the PASS CIRCUITRY in the POWER UNIT.

B. COMPARISON AMPLIFIER CIRCUITRY:

(1) The COMPARISON AMPLIFIER consists of a series of cascaded transistor amplifiers which boost the "error input" to a sufficient level to drive the PASS CIRCUITRY in the POWER UNIT.

(2) The COMPARISON AMPLIFIER is connected across the COMPARISON BRIDGE from the junction of the VOLTAGE CONTROL and the REFERENCE RESISTANCE to the junction of the Zener reference diode and the negative output terminal. (See Diagram B-2). This arrangement is similar to that of the null galvanometer across a Wheatstone bridge. The unbalance in the COMPARISON BRIDGE is detected and amplified by the COMPARISON AMPLIFIER CIRCUITRY beginning a chain of circuit responses which produce an ERROR INPUT signal of proper phase and magnitude to effect corrective action by the pass circuitry.

.....III. Comparison Bridge:

(1) This bridge circuit implements the comparison between the OUTPUT VOLTAGE and the REFERENCE VOLTAGE. The signal produced by the comparison drives the COMPARISON AMPLIFIER CIRCUITRY.

(2) The Comparison Bridge is represented schematically in Diagram B-2.

(3) Balance occurs in the Comparison Bridge when the following ratios are equal:

$$\frac{\text{Output Voltage}}{\text{Voltage Control Resistance}} = \frac{\text{Reference Voltage}}{\text{Reference Resistance}}$$

(4) When the Comparison Bridge is unbalanced by a decreasing output voltage drop across the load, it gives rise to a negative bias at the base of the COMPARISON FOLLOWER in the COMPARISON AMPLIFIER CIRCUITRY. This signal, amplified, acting as the ERROR INPUT negatively biases the base of the DRIVEN PASS, aiding its forward conducting bias and increasing the output voltage.

(5) A bridge unbalance caused by an increasing output voltage produces, of course, a chain of oppositely biased circuit responses which reduce the voltage across the load.

INSTRUCTION MANUAL

VOLTAGE REGULATED POWER SUPPLY

MODEL HB 8M

SERIAL NO. . . . . .

STANDARD POLICY COVERING REPRODUCTION AND USE OF TECHNICAL DATA FOR KEPCO MANUFACTURED EQUIPMENT

The technical data submitted, including manuals, parts information, and mechanical and electrical drawings, is furnished solely for the purpose of effecting maintenance and/or repairs to the apparatus therein described and the purchaser or the Government shall not reproduce, use, or disclose the said technical data, in whole or in part, for any other purpose. Such technical data shall not be used for promotional procurement, development or manufacturing purposes, nor shall the purchaser or the Government permit the reproduction, use, or disclosure of any part of said technical data by others. The purchaser shall notify the Government of the purchaser's limited right in the use of said technical data for aforesaid purposes. In the event that any part of this technical data is used by anyone for other than the above authorized purposes, the purchaser will give all assistance possible for the prosecution of action against any unauthorized use thereof.

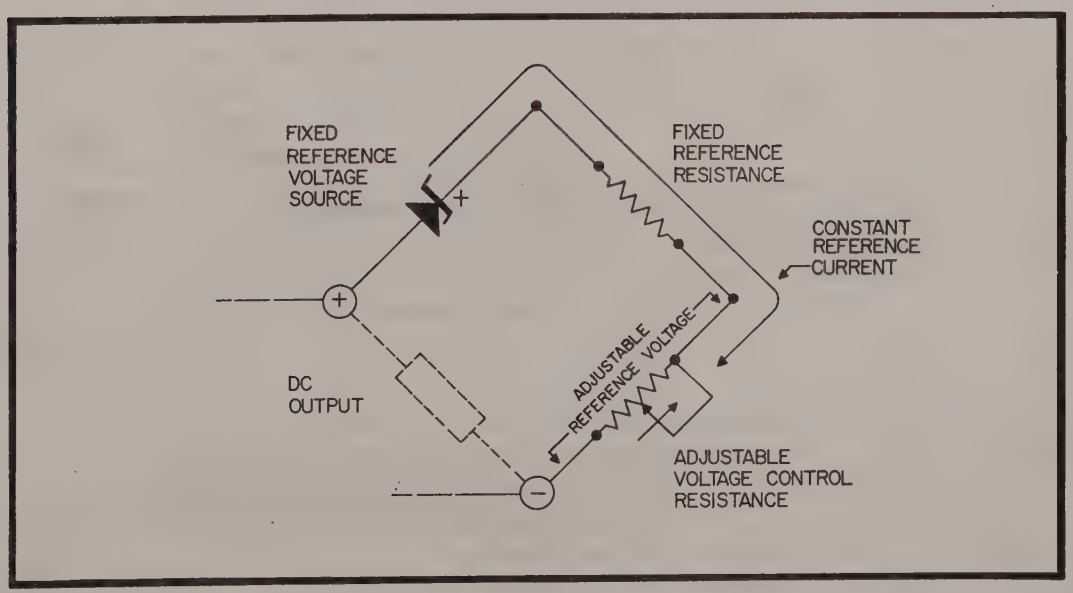
SECTION B THEORY OF OPERATION AND CIRCUIT DESCRIPTION

B-1. THEORY OF OPERATION.

.... This Kepco Voltage Regulated Power Supply consists essentially of a fixed, unregulated DC power source, followed by a Series Regulator in a closed feedback loop. The closed loop system is designed to permit the voltage at the output terminals to be set to any value over a continuously adjustable range, and to maintain that output voltage constant, within the specified percentage of regulation, as the line voltage or load change in value.

.... All of the current drawn by the load flows through the Series Regulator, which is the plate path of a power pentode Pass Tube Circuit. The effective impedance of the Pass Circuit and its voltage drop is determined by the grid bias of the Pass tube, and this voltage drop can be adjusted or controlled by a Control Signal applied as a bias to the grid. The voltage at the output terminals will be equal to the unregulated DC source voltage minus the voltage drop across the Pass Circuit. Therefore, the output voltage can be stabilized by controlling the Pass Circuit voltage drop.

.... A stable, adjustable reference voltage, equal to the desired output voltage, is established in one side of a bridge-like Comparison Circuit by means of a Zener-diode-controlled Fixed Reference Voltage source, in conjunction with an adjustable Voltage Control Resistance.



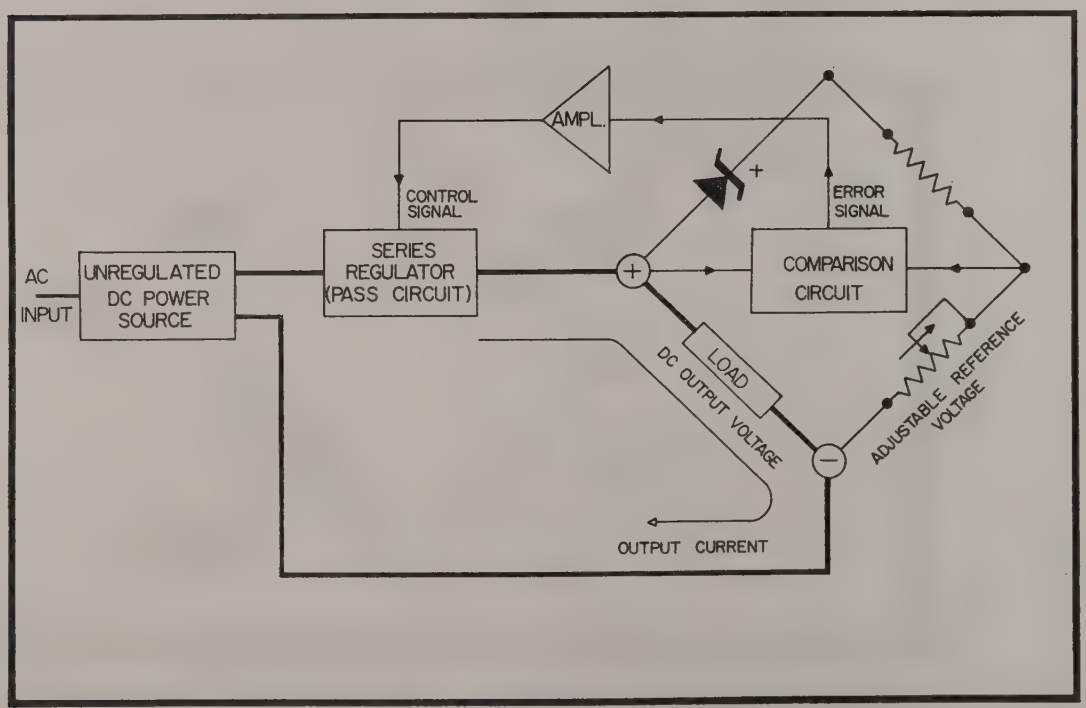
Simplified Circuit Diagram of the Reference Voltage Circuit.

.... The instantaneous value of the output voltage is compared to the adjustable reference. It is applied to the Comparison Circuit so that an Error Signal results, as the difference between the output voltage and the established reference voltage. The Error Signal, amplified, becomes the Control Signal for the Pass Circuit.

.... The closed feedback loop includes the voltage drop in the Pass Circuit, the output voltage, the Error Signal output of the Comparison Circuit, and the amplified Error or Control Signal applied to the grid of the Pass Circuit tube.

.... A condition of equilibrium is considered to exist around the closed feedback loop when the Output Voltage is equal to the desired value, and which, when compared to the reference, develops a Control Signal of the correct value necessary to produce the required voltage drop in the Pass Circuit.

.... Any tendency in the output voltage to change (such as from the result of a change in line voltage or load impedance), from the requisite value as established in the Comparison Circuit by the setting of the Control Resistance, will be detected in the Error Signal. Through the action of the Control Signal, the Error Signal will effect the necessary change in the voltage across the Pass Circuit required to maintain the output voltage constant and maintain equilibrium around the closed loop.



Simplified Circuit Diagram of Closed Feedback Loop, Series Regulated Power Supply.

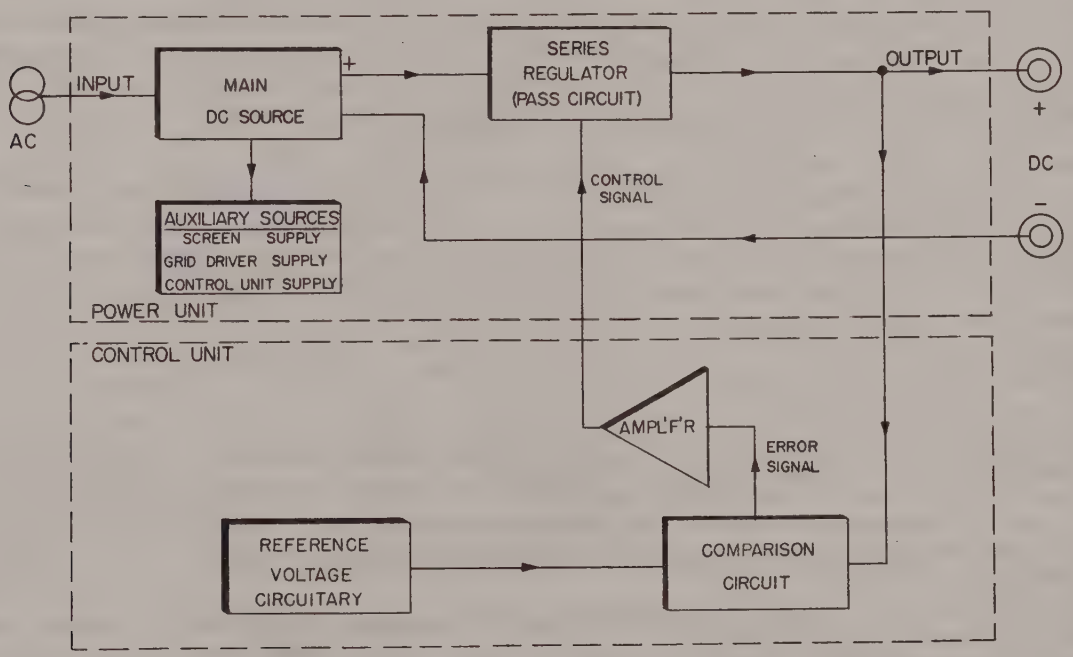
B-2 CIRCUIT DESCRIPTION

....This Kepco Power Supply is composed of two main electrical subdivisions, the Power Unit and the Control Unit.

The Power Unit includes the Power Input, the Main and Auxiliary DC Sources, the Series Regulator Pass Tubes, and the adjustable Voltage Control.

The Control Unit includes the Reference Voltage Circuitry, the Comparison Circuit, and the Control Signal amplifier.

Separate Schematic Diagrams for the Power and Control Unit are provided in the Appendix section of the Instruction Manual, and the Parts List in the Appendix is subdivided on the same basis. Capitalized terms refer to components or circuits as they are labelled on the Schematic diagrams.



BLOCK DIAGRAM—SERIES REGULATED DC POWER SUPPLY

....POWER UNIT.

MAIN DC SUPPLY. - The unregulated DC Power Source which furnishes power to the output terminals through the Series Regulator. In any given output range, the DC Source is designed to provide a nominally fixed DC supply voltage greater than the maximum output voltage of that range, by an amount equal to the voltage drop required across the Series Regulator Pass Circuit. The supply voltage for each output range is selected by the

Voltage Range Switch, at the secondaries of the Main DC Supply transformer. The DC Supply is full wave bridge rectified, with high capacitive filtering.

SCREEN SUPPLY. - Furnishes DC voltage, separate from the Main Supply, for the screen grids of the Regulator Pass Tubes. Full wave bridge rectified and filtered.

GRID DRIVER SUPPLY. - Separate negative DC supply provides collector voltage for the grid driver transistor in the Control Unit, and bias voltage for the grid of the Pass Tubes.

CONTROL UNIT SUPPLY. - Separate DC supply for the Control Unit circuitry, including the Fixed Reference Voltage, Comparison Circuit, and Control Signal amplifiers.

SERIES REGULATOR. - Contains two or more power-pentode Pass Tubes in parallel, depending on the output current rating of each model. The amplified Control Signal derived from the Comparison Circuit in the Control Unit is applied to the grids of the Pass Tubes.

ADJUSTABLE VOLTAGE CONTROL. - Consists of the continuously adjustable Fine Voltage Control, a potentiometer, in series with a fixed resistance selected by a section of the Voltage Range Switch. Constitutes the adjustable element in establishing a reference to which the output voltage is compared.

....CONTROL UNIT.

REFERENCE VOLTAGE CIRCUITRY. - Powered by DC voltage from the Control Unit Supply in the Power Unit. Produces a Zener diode stabilized, Fixed DC Reference Voltage source for the Comparison Circuit, and stabilized DC voltages for the transistor amplifiers in the Control Unit.

COMPARISON CIRCUIT. - Implements a differential comparison between a reference voltage representing the voltage to which the output of the supply is set, and the voltage across the output terminals. The Fixed Reference Voltage source, in conjunction with the Fixed Reference Resistance, produces a constant current through the adjustable Voltage Control Resistance. The difference voltage between the voltage across the output terminals and the voltage across the Voltage Control Resistance is the Error Signal, which is amplified and fed back to the Series Regulator Pass Circuit. The Error Signal voltage is detected initially in the Comparison Follower stage.

COMPARISON AMPLIFIER. - A series of cascaded transistor stages including the Comparison Follower which amplify the Error Signal to a level sufficient to drive the control grids of the Regulator Pass Tubes.

GENERAL TROUBLE-SHOOTING LOGIC

by: DR. KENNETH KUPFERBERG
Director of Engineering

The OBJECT of this paper is to acquaint the general service technician with methods developed by Kepco, Inc. for trouble shooting closed-loop systems in general, and regulated power supplies in particular. These methods, based on simple circuit logic, provide a reliable means of locating defective components in a regulator system. The concept of a transistor acting as a switch will be introduced and briefly developed for trouble-shooting transistorized power supplies.

TRANSISTORS: A transistor is a three terminal device consisting in essence of two semiconductor diodes symmetrically joined, sharing a common (base) region. The device is normally biased to aid forward conduction in one diode (emitter diode) and oppose forward conduction in the other (collector diode). (See Fig. 1) When the bias of the forward conducting diode (emitter diode) is varied about the quiescent operating point, an amplified version of this variation appears across the transistor's collector-emitter terminals.

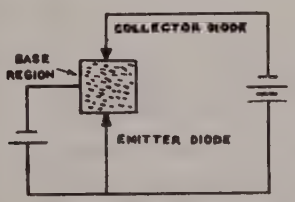


Fig. 1:

TRANSISTOR AS SWITCH: If the base emitter bias current becomes so large that further increase in this current does not increase the collector current, the transistor is said to be saturated. A saturated transistor which conducts maximum collector current with minimum voltage drop is equivalent to a closed switch. In a PNP transistor this condition occurs if the base to emitter voltage is negative in polarity and ≈1 volt or larger in magnitude.

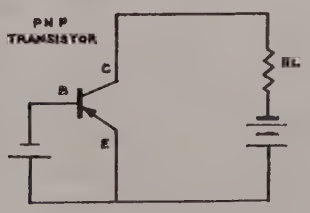


Fig. 2:

If the base to emitter bias is very small or the reverse of the forward conducting polarity, the collector current becomes practically zero, and the transistor is effectively shut off. This condition is analogous to that of an open switch. This cutoff condition in a PNP transistor occurs if the base to emitter voltage is zero or positive.

VOLTAGE REGULATED POWER SUPPLIES: A closed-loop voltage regulating system has three main interdependent subsystems corresponding to the elements in Fig. 3.

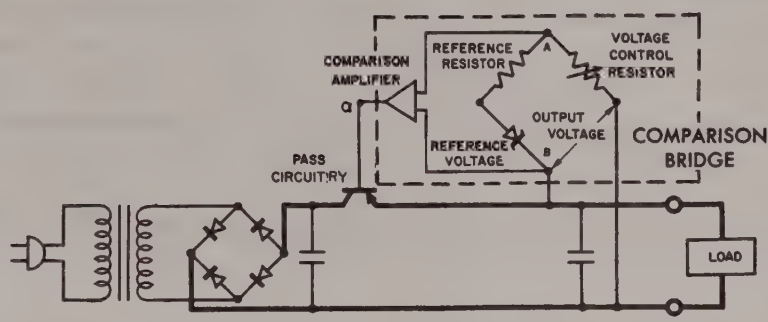


Fig. 3: Voltage Regulated Power Supply.

1. COMPARISON BRIDGE as shown in Fig. 4 provides a continuous comparison of the power supply output with a stabilized REFERENCE VOLTAGE. Any difference or "error signal" is fed to the COMPARISON AMPLIFIER.

2. COMPARISON AMPLIFIER provides enough amplification for the error signal to drive the PASS CIRCUITRY. The gain of the COMPARISON AMPLIFIER, plus the gain of any additional driver stages in the Pass Circuitry, largely determines the sensitivity of the system to output variations. The amplified ERROR SIGNAL is called the ERROR INPUT. In the case of transistor Pass Elements the ERROR INPUT is to the base terminal.

3. PASS CIRCUITRY. The Pass Elements are in series with the output in what might be called the "power stage" of the closed-loop system. The series resistance of the Pass Element varies as a function of the magnitude of the ERROR INPUT. The ERROR INPUT is a negative feedback signal and consequently, the resistance changes it produces are such as to oppose the direction of the output voltage changes which produce the ERROR SIGNAL. As a result, the voltage drops across the "power stage" are always distributed in such a way that the Pass Elements "absorb" the effects of line or load variations and thereby allow the output voltage to remain relatively unaffected.

A GENERAL PHILOSOPHY OF TROUBLE-SHOOTING CLOSED-LOOP SYSTEMS:

1. A fundamental inconsistency in circuit logic has to be established: namely, that the output voltage is either too high or too low with respect to the voltage control setting. Before trouble shooting is attempted the direcion of this deviation *must* be known.

2. The inconsistency in circuit logic has to be localized in the system. This can be achieved in two ways:

a) By taking voltage measurements at strategic check points.

b) By breaking continuity in the circuit at strategic points and simulating the control signal with an outside source.

A strategic check point is defined as a junction in the circuit where one measurement would tentatively eliminate at least one possibility of defect among the subsystems. The junction C of the control signal amplifier and the pass circuitry is such a strategic point, because if the signal at this point is correct, it means that the trouble is somewhere in the pass circuitry; if the signal at this point is incorrect, it means that the trouble is either in the amplifier or in the comparison bridge. A successive measurement at the next strategic point, which is junction A of the amplifier and the comparison bridge, would point to one or the other subsystems as being defective.

For ex. the output voltage is too high and there is no control. A voltage measurement at the junction C of the control signal amplifier and pass circuitry indicates a positive voltage with respect to the negative output terminal. If the pass elements in this particular power supply are PNP transistors, then this is the correct signal at this junction, because this voltage would reverse bias the PNP junction of the transistors in the pass circuitry and cut off pass elements in an attempt to reduce output voltage of the supply as discussed above. (PASS CIRCUITRY) However, a symptomatic high output voltage measurement, even though the control signal is attempting to cut off the pass circuitry, indicates a defective component in the pass circuitry subsystem and hence an inconsistency in circuit logic.

3. The component that is the cause of this inconsistency in circuit logic has to be pinpointed. Successive voltage measurements at the bases of the driver transistors in the pass circuitry subsystem should locate the defective stage from whence simple voltage and resistance measurements will locate the defective component quickly.

SUMMARY: In order to systematically trouble-shoot a closed loop feedback system ... An inconsistency in circuit logic has to be established. It must be determined that the output voltage is too high or too low for corresponding settings of the voltage control.

... The breakdown in circuit logic has to be traced to the subsystem involved by taking measurements at strategic junctions.

... The defective stage has to be located by methods based on the concept of the *TRANSISTOR AS A SWITCH.*

By approaching the circuit in an orderly methodical fashion, the cost and time consumed in routine trouble-shooting, maintenance and calibration can be substantially reduced.

KEPCO INC. FLUSHING, N.Y.	QUALITY CONTROL PROCEDURE-SPECIFICATION	NO. A Q5-0022
		DATE 8-26-60

TITLE: TEST PROCEDURE; REGULATION AND RIPPLE MEASUREMENT

DESCRIPTION

Formerly: AF00167; "Regulation and Ripple Measurement Specification" 8-26-60; 4 pages

I. Equipment List
II. Procedure for Measuring Line Regulation
III. Procedure for Measuring Load Regulation
IV. Procedure for Measuring Ripple

APPROVAL	
DRAWN AM / EF	CHECKED HH
APPROVED	DATE 9/1
APPROVED	DATE

REVISIONS	BY	APPROVED		DATE

DISTRIBUTION	QUAN
Gen'l. Mgr.	
Dir. Eng'g.	2
Plant Mgr.	
Purch. Eng'r.	
Bldg. Eng'r.	
Quality Control	1
Inspection	
Test	1
Prod. Mgr.	
Prod. Eng.	1
Prototype Eng'g.	1
Magnetics	
Sales Eng'g.	
Customer S'vce.	1
Publications	
Stockroom	
Shipping	
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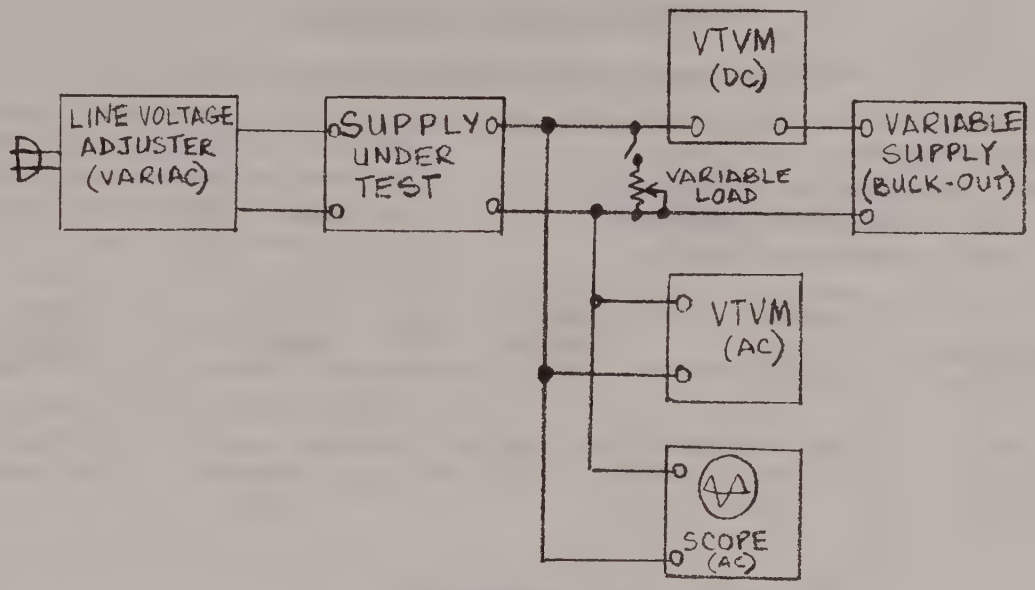


EQUIPMENT LIST

1. Line Voltage Adjuster- Variable Autotransformer capable of adjustment through the rated input voltage range of the supply under test. Also must have sufficient power handling capability to operate supply under test, and do this without sig - ificant changes in output when load current is changed; otherwise, readjustment is required after each load change.

2. DC VTVM - Must have sensitivity of at least 10 millivolts DC full scale and input impedance of at least 10 megohms.

3. Variable Supply (Buck-out) - May be another power supply. Must have good short-term stability and line regulation of the same order of magnitude of the supply under test. Since practically no load current is drawn fromt it, current requirements are negligible. Output voltage must be capable of adjustment through same output range or greater than the output range of the supply under test. Resolution of settings must be equal to or greater than the magnitude of measurement expected; e.g., to measure3 mv devation the supply should be capable of at least 1 mv resolution.

4. AC VTVM - Sensitivity of at least 1 millivolt RMS

5. AC Scope - Sensitivity of at least 1 millivolt/cm.

6. Variable load & Switch - With sufficient voltage & current ratings suitable for supply under test.

NOTE: The instrumentation described in this specification is only one of many possible methods. Alternate suggestions for regulation measurements are Calibration Standards Model RM-4A Regulation Monitor or Kepco Model 901B Regulation Analyzer. In either case, manufacturer's instructions should be followed.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

DRAWN	CHECKED	APPROVED	DATE	KEPCO INC.
MM / EF	—MM—		8-26-60	FLUSHING, N.Y.
MODEL NO.		PART NO.	SCALE NTS	
TITLE REGULATION & RIPPLE MEASUREMENT SPECIFICATION			DWG. NO. A Q5-0022	SHEET 1 OF 4

Line Regulation Measurement:

A. Three measurements are made as follows:

SETTINGS			Adjust buck-out supply to null DC VTVM (zero volts) at either limit of supply's Line Voltage Rating for each measurement; then:	
Measurement	Output Voltage	Output Current	VARY ⬇	READ ⬇
1.	MAX. RATING	MAX. RATING	Line Voltage through rated range	Change in voltage on DC VTVM
2.	$\frac{\text{MAX.} + \text{MIN.}}{2}$	"	"	"
3.	MIN. RATING*	"	"	"

B. The highest reading (worst case)of the three values of voltage change obtained is considered the Line Regulation of supply under test.

* = If minimum rated output voltage is zero , take measurement at an output voltage slightly higher than zero, as this facilitates loading the supply.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

DRAWN	CHECKED	APPROVED	DATE
EF	-MM-		8-29-60

MODEL NO.	PART NO.	SCALE

KEPCO INC.
FLUSHING, N.Y.

TITLE REGULATION & RIPPLE MEASUREMENT SPECIFICATION

DWG. NO. AQ5-0022 SHEET 2 OF 4

Load Regulation Measurement:

A. Three measurements are made as follows:

SETTINGS:			Adjust buck-out supply to null DC VTVM (zero volts), at either no load or max. rated load current for each measurement; then:	
Measurment #	INPUT VOLTAGE (LINE)	OUTPUT VOLTAGE	VARY ⬇	READ ⬇
1.	NOMINAL RATED	MAX. RATED	Load current between 0 and Max. rated current	Change in voltage on DC VTVM
2.	"	$\frac{\text{MAX.} + \text{MIN.}}{2}$	"	"
3.	"	MIN. RATED*	"	"

B. The highest reading (worst case) of the three values of voltage change obtained above is considered the Load Regulation of the supply under test.

* = If minimum rated output voltage is zero, take measurement at an output voltage slightly higher than zero, as this facilitates loading the supply.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

DRAWN	CHECKED	APPROVED	DATE	KEPCO INC. FLUSHING, N.Y.
EF	-MM-		8-29-60	
MODEL NO.		PART NO.	SCALE	
TITLE REGULATION & RIPPLE MEASUREMENT SPECIFICATION			DWG. NO. AQ5-0022	SHEET 3 OF 4.

Ripple Measurement:

A. Two measurements are made as follows:

Measurement #	Input (Line) Voltage	Output Voltage	Output Current	READ
1.	MAX. RATING	MIN. RATING	ZERO	Ripple voltage directly on AC VTVM.
2.	MIN. RATING	MAX. RATING	MAX. RATING	"

B. The highest reading (worst case) of the two values of ripple obtained above is considered the Ripple of supply under test.

C. Peak-to-peak ripple measurements and oscillation checks may be made simultaneously with the above tests by using the AC oscilloscope.

NOTE: Caution must be taken to establish that lead connections do not affect accuracy of readings on all tests covered by this specification. This is especially true of heavy current supplies. On models with rear output terminations, load and instrumentation are to be connected at rear. If separate error signal and load terminals are available at rear, instrumentation is connected directly at error signal terminals and load is connected to load terminals.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

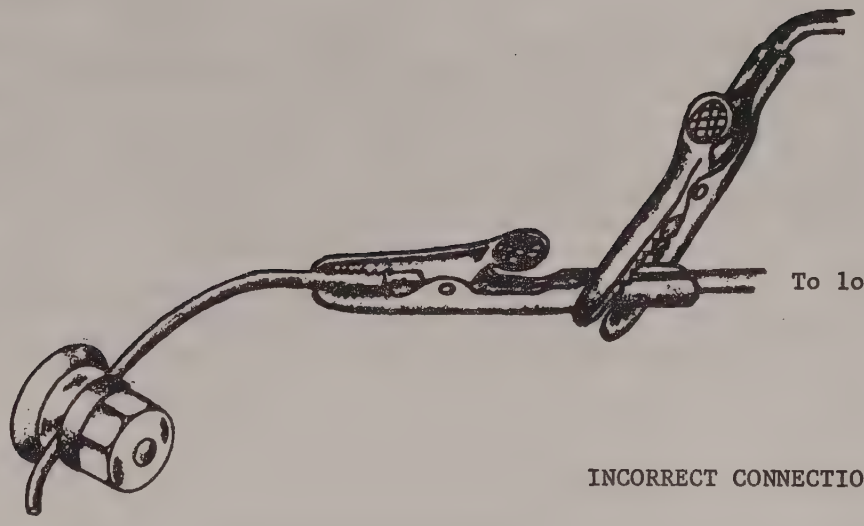
DRAWN	CHECKED	APPROVED	DATE
EF	-MM-		8-29-60
MODEL NO.		PART NO.	SCALE NTS

KEPCO INC.
FLUSHING, N.Y.

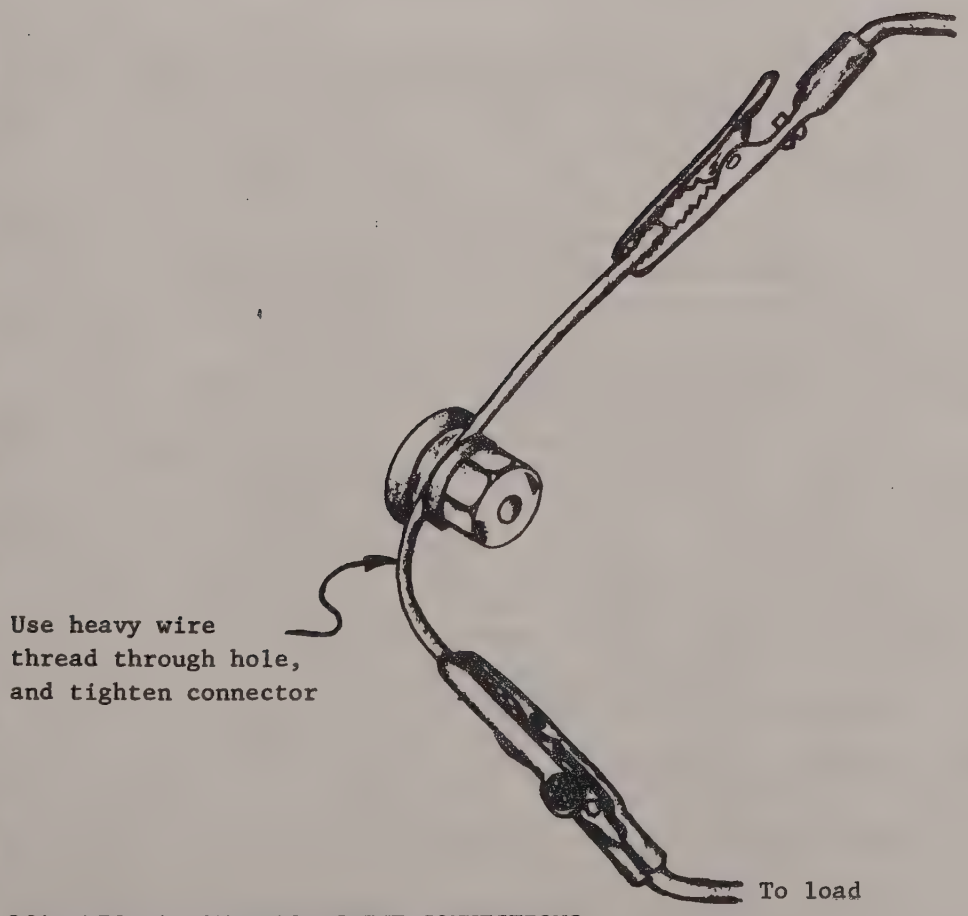
TITLE REGULATION & RIPPLE MEASUREMENT SPECIFICATION

DWG. NO. A Q5-0022 SHEET 4 OF 4

DEFIANCE NO. 1000H 35731



INCORRECT CONNECTIONS



CORRECT CONNECTIONS

LOAD REGULATION MEASUREMENT CONNECTIONS

KEPCO INC. FLUSHING, N.Y.	QUALITY CONTROL PROCEDURE-SPECIFICATION	NO. AQ5-0020 1 of 3
		DATE 5-25-60

TITLE TEST PROCEDURE: DYNAMIC IMPEDANCE MEASUREMENT

DESCRIPTION

Formerly: BF00122; "Test Specification for Dynamic Impedance Measurements"; 5-25-60; 1 page.

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Test	✓
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DYNAMIC OUTPUT IMPEDANCE MEASUREMENT

I. The Dynamic Output Impedance of a DC Power Supply expresses in ohms, the effective impedance as indicated by the measured change in output voltage resulting when the output current is changed at a constant sinusoidal frequency. It is usually measured at several different frequencies in order to plot a characteristic curve of output impedance over a useful range of frequencies. A method of measuring Dynamic Output Impedance is described here, in which the output current of the Power Supply is sinusoidally modulated at 10% of maximum rated current, and the peak to peak values of current (I_{p-p}) and voltage (E_{p-p}) are measured, at different modulating frequencies. From these measurements, the output impedance (Z_o) is calculated by:

$$Z_o = \frac{E_{p-p}}{I_{p-p}}$$

II. DESCRIPTION OF INSTRUMENTS USED: (Refer to set up diagram)

A. Kepco Model 920B, Line Voltage Adjuster-Stepper.
B. Power Supply under test.
C. Kepco Model 910B, Variable Load.
D.E. Tektronix Model 502 Oscilloscopes.
F. Vacuum Tube Voltmeter.
G. Hewlett Packard Model 200 CP Sine-Wave Generator.
H. Meter Shunt, 10 A, 50 mv; non-inductive.
R.1 Kepco Model 6212, Variable Resistive Load.

III. PROCEDURE:

1. Set Line Voltage with "A" to 115 volts.
2. Set the output voltage of the Supply under test, as measured with Voltmeter "F", to the Supply's rated maximum output voltage or 600 v, whichever is less.
3. Adjust Load R 1 to draw 90% of the rated maximum output current of the Supply under test, as measured by Ammeter A 2.
4. The load is modulated with Variable Load "C". Set Variable Load "C" to modulate the output of the Supply under test, with a sinusoidal current equal in peak-to-peak value to 10% of the rated maximum output of the Supply, or 500 ma (peak-to-peak) whichever is less. (See Output Current Waveform Diagram). The modulating frequency of Variable Load "C" is obtained from the Sine-Wave Generator "G".
5. Unless otherwise specified, measurements will be made over the total range of 10 cycles to 100 kilocycles; at each subsequent octave in that range beginning with 10 cycles. Where critical portions appear in any part of the curve, measurements should be made at a sufficient number of frequencies between octaves to plot an accurate curve.
6. Calculate the impedance for each point of measurement in accordance with the formula described in (I) above.
7. Precautions must be taken in the instrumentation set-up to insure the accuracy of the readings.
   a. 1 R drops in leads and connections that may affect accuracy must be avoided.
   b. On models with rear output terminals, connect load and instrumentation to these.
   c. On models with separate error-sensing terminals, connect instrumentation to these, and the load to the rear output terminals. (Error sensing jumpers in place.)

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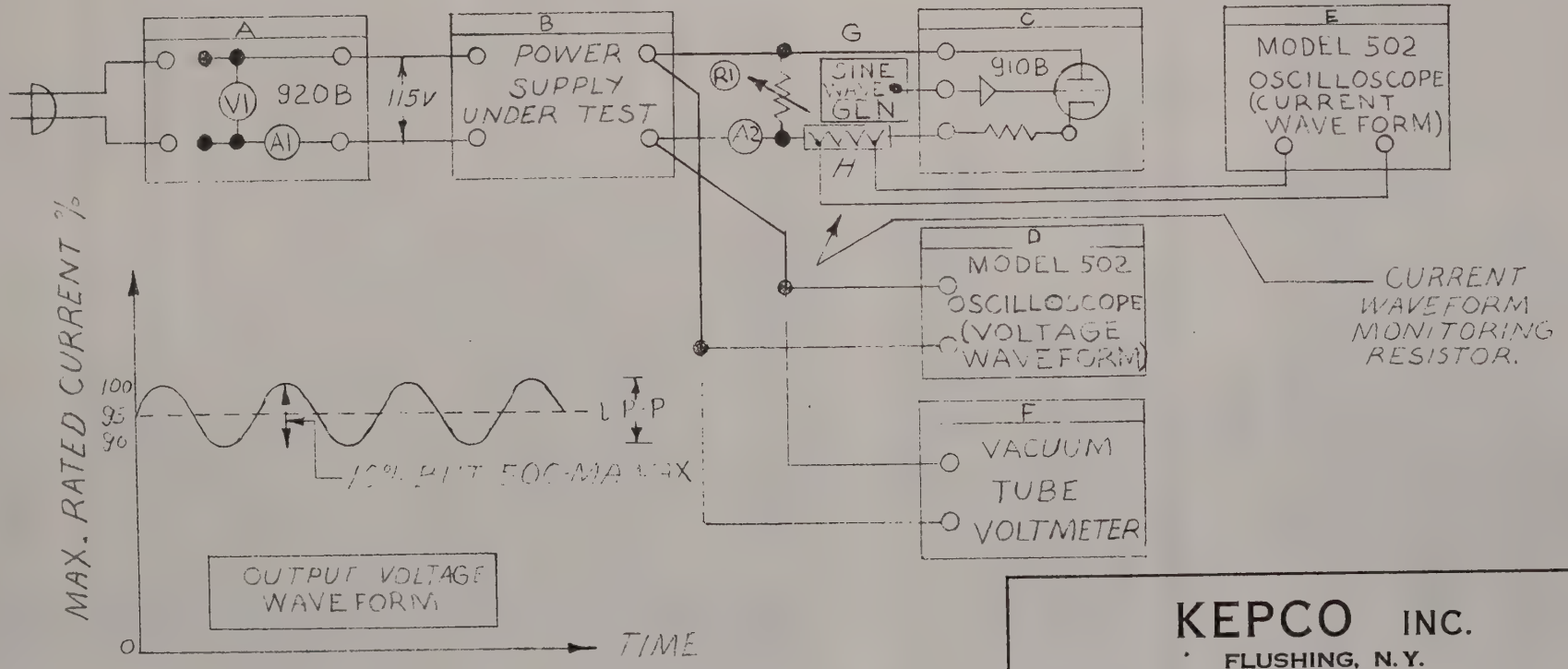

KEPCO INC.

FLUSHING, N.Y.

TITLE: TEST SPECIFICATION FOR DYNAMIC IMPEDANCE MEASUREMENTS

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MODEL NO.		PART NO.	SCALE

DWG. NO. A Q5-0020 PAGE 3 OF 3

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

KEPCO INC. FLUSHING, N.Y.	QUALITY CONTROL PROCEDURE-SPECIFICATION	NO. A Q5-0077
		DATE 12-14-62

TITLE PROCEDURE, TRANSIENT POWER SUPPLY MEASUREMENTS

DESCRIPTION

SCOPE: The Purpose of this procedure is to standardize the way in which transient response (recovery time) is defined and measured.

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Definition:

Recovery Time specifies the time required for the output voltage to return to a value within the regulation specification after a step load or line change.

Response Time (time constant) specifies the time required for the voltage excursion to be reduced to 37% of its peak value after a step load or line change.

Alternate: Transient response can be specified as the time required for the voltage excursion to be reduced to a specified minimum voltage.

Note: Unless otherwise specified by Engineering for a particular design, the definition of RECOVERY TIME will be employed in making all transient measurements.

Transient measurements should be made at maximum output voltage (where practical) and with a maximum current step load.

Equipment: Oscilloscope - Tektronix 545 or equivalent
Oscilloscope Camera - Dumont type 302 or equivalent.
Switching Device Kepco Model 910B
Model 6324-910B
Model 6265
Model 6523
Model 6342
or equivalent electronic load with jitter-free, transient free, 10-100 microsecond rise time and fall time.

Note: Where power supply output exceeds rating of available electronic load, resistive loads should be used with equivalent jitter-free switching. Alternatively, measurements can be made at less than full output voltage at the discretion of the engineering department.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

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KEPCO INC.
FLUSHING, N.Y.

TITLE Procedure, Transient Power Supply Measurements

DWG. NO. A 05-0077

PROCEDURE:

1. Connect electronic load to the power supply output terminals closest to the error sensing connections and adjust for 0-full load-0 load steps at a 60 cps rate or other convenient repetition rate whose period is much longer than the expected power supply response.

2. Observe the output voltage at the power supply terminals with the oscilloscope set for AC coupling and appropriately calibrated vertical sensitivity and horizontal time-base. When observing partially regulated or other long response time power supplies, employ DC oscilloscope coupling with a buck-out voltage to allow adequate voltage sensitivity.

3. Record peak excursion and time required for recovery on test form.

4. Photograph oscilloscope trace, mark with calibration settings and attach to test form.

5. Record Model and serial number information.

TOLERANCE UNLESS OTHERWISE SPECIFIED: FRACTIONS ± 1/64 DECIMALS ± .005 ANGLES ± 1/2°

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KEPCO INC.
FLUSHING, N.Y.

TITLE Procedure, Transient Power Supply Measurements

DWG. NO. A Q5-0077

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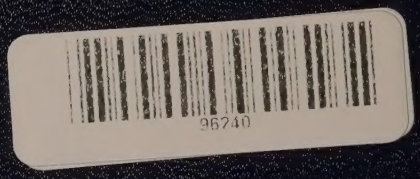
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